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THE UNIVERSITY OF ALBERTA

PREDICTION OF TRACTOR PERFORMANCE IN THE FIELD

by

© ZHAOWEI WANG

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

EDMONTON, ALBERTA

FALL 1988

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K. W. Domier
.....
Supervisor

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Date 1988-07-13

ABSTRACT

A Case International model 2394, two wheel drive tractor equipped with dual tires, and a 7.6 metre wide chisel plow was instrumented with an on-board data acquisition system. The instrumented tractor was used in the Fuel Use Demonstration Project conducted by Alberta Agriculture and Olds College. The instrumentation enabled the monitoring of drawbar pull, fuel consumption, ground speed, wheel speed, engine speed, and implement depth. As a part of the project, the equipment was used over a wide range of field conditions in Alberta in the spring and summer of 1987. Meanwhile, the soil cone index and the soil shear strength parameters were measured on sixty-three fields.

A computer model has been developed to predict the tractive performance, the tractor-implement combination performance, and the energy requirements for an agricultural tractor in tillage operations. The model considers the engine characteristics, tire characteristics, tractive performance, implement characteristics, and soil properties, that combine to represent the physical tractor working in an agricultural field. The drawbar performance was predicted by two approaches. The first approach was based on cone index only and the second approach was based on a combination of cone index and soil shear parameters. The difference between predictions for approach I and approach II was not significant for dual tires.

The computer model of two wheel drive tractor with dual tires was validated by using the field test data obtained in the project and a good agreement between predicted and measured performance was obtained.

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1. INTRODUCTION

1.1 Background of Tractor Performance Study

Traction study is the most important part in tractor performance. Traction may be defined as the force derived from the interaction between a traction device and a medium, usually soil in agriculture, which can be used to facilitate a desired motion over the medium (Gill and Vanden Berg, 1968). The traction device converts rotary motion generated by an engine into useful linear motion. The dynamic resistance of the medium or soil at the interaction provides the traction. A part of the force is wasted in overcoming the motion resistance and the rest, which remains as a useful force to accelerate the vehicle, climb the slope, or pull a load, is call tractive effort.

The traction device for an agricultural tractor has included rigid wheels, tracks, and pneumatic tires. The early traction device of an agricultural tractor was steel wheels. To achieve a better tractive performance, grousers were mounted on the wheels. Many years later, the steel wheels were replaced by pneumatic tires and steel tracks which have better traction characteristics. The steel track gradually disappeared in agricultural fields because of poor road characteristics and slow travel speeds. Nowadays the traction devices of agricultural tractors are dominated by pneumatic tires.

The tractive performance of an agricultural tractor is affected by both the physical design of the tractor and the physical characteristics of the soil. The study of traction did not make real progress until the development of soil-vehicle mechanics although the importance of soil to tractive performance has been known for many years. Soil dynamics research had been conducted only since 1920. Until that time no concerted effort was made to bring information together and use research along fundamental lines to solve complex problems in traction and tillage (Gill and Vanden Berg, 1968). Since then, considerable effort has been put into the study of soil-vehicle mechanics and great progress has been made. The current approaches to the problems involved may be listed in the following groups:

1. A theoretical approach based on civil engineering soil mechanics.
2. An analytical approach using semi-empirical soil stress deformation relationship.
3. Index system based on attempting to describe soil characteristics by means of a single simple measuring device.
4. Model experiments using dimensional analysis to systematize the results.
5. A rigorous mathematical approach based on the theory of plasticity.
6. Model the interaction between the traction device and soil by use of the finite element method.

Fuel consumption as an indicator of energy requirement of a tractor is also an important parameter in tractor performance study. Fuel consumption of a tractor is affected by engine characteristics, the transmission, the load, the tractive performance, and the fuel used.

To obtain the optimum performance from an agricultural tractor, an understanding of the interaction between the wheel and the soil on which the wheel operates is necessary. The interaction between pneumatic tire and deformable soil, however, is very complex since the geometry of the wheel and the soil both change during dynamic operation.

Use of the field test as one of the features of tractor performance study has been popular for decades. Many empirical relationships and characteristics of tractor performance have been discovered based on experiments. The modeling and computer simulation of tractor performance, on the other hand, has long been of interest to both engineers and farmers, especially since the application of the computer was introduced to agriculture. Tractor performance is dependent on load, soil, speed of operation, and the physical design of the tractor. Therefore, to model and simulate the tractor performance, a number of factors need to be considered.

The simplest model of the tractor tire-soil interaction is obtained by assuming a rigid wheel operating on a hard surface, which, however, is far from real tire and soil conditions and therefore, can not closely estimate the

tractive performance of a tractor working in the field. An exact model of the pneumatic tire-soil system has not been accomplished yet. The existing models involve simplifying assumptions which allow the model to produce a useful solution with limited accuracy. Furthermore, as noticed by Macnab (1976), computer modeling and simulation allow the engineer to do hypothetical field testing and to determine trends which result from changing the model input parameters although the results obtained from the prediction are only estimated. The tractor performance can be studied by computer simulation without incurring the cost, time and machinery allocation that otherwise would be necessary for extensive field testing of various tractor implement combinations over a wide range of operating conditions.

1.2 Purpose and Scope of the Study

The study had three purposes as follows:

1. To develop a computer program for modelling tractive performance and energy requirement. Two approaches for soil strength parameters were employed. The first was based on cone index only and the second was based on a combination of cone index and shear strength parameters. The second approach was aimed at improving the accuracy of the prediction since more soil parameters could be utilized. The two approaches were compared.
2. To model the tractor-implement combination performance. A two wheel drive tractor with dual tires and towed

implement system was examined.

3. To validate the models in the above two purposes. The field test data for the two wheel drive tractor with dual tires were collected as part of the project conducted by Alberta Agriculture and Olds College to develop a data base and to demonstrate fuel usage during field operation.

1.3 TERMINOLOGY

The report has used many terms, the meanings of which may differ from the common definitions. Although most of the terms can be found in ASAE Standards (1986), the definitions of some terms may vary depending on the particular author. To avoid misunderstanding, the definitions of some important terms are listed as follows:

1.3.1 Soil strength terms

1. Cohesion(c): The shear strength of a soil at zero normal pressure. Cohesion c is one of the Coulomb's shear strength parameters.
2. Internal friction angle (ϕ): The slope angle of the shear stress versus normal pressure curve. ϕ is the other Coulomb's shear strength parameter.
3. Deformation modulus (K): The distance between the abscissa and the point of intersection of two straight lines tangent to both the sloped and the horizontal portion of the shear stress versus soil deformation

curves. Usually, the K value is determined directly from the shear curves. (Bekker, 1969)

4. Cone penetrometer: A 30° circular stainless steel cone with driving shaft. The design and the test procedure are discussed in ASAE S313.2.
5. Cone index (CI): The force per unit base area required to push the penetrometer through a specified increment of soil. The value at a certain depth or the average value over a range of depth may be reported. (ASAE S313.2)

1.3.2 Pneumatic tire terms

1. Diameter (D, no load): Tire circumference measured over the lugs in the center plane divided by π with the tire mounted on the normal rim and inflated to recommended operating pressure. (ASAE S296.2)
2. Section width (b): The width of a tire including normal growth caused by inflation pressure.
3. Deflection (δ): The change in tire radius from unloaded to loaded conditions.
4. Effective rolling radius (r_d): The distance traveled per revolution divided by 2π. It can not be measured directly. (Charles, 1984)
5. Loaded radius (r): Tire radius under load which can be obtained by subtracting the deflection from the unloaded radius.

1.3.3 Tire-soil system terms

1. Gross traction or thrust (H): Input torque divided by effective tire radius.(ASAE S296.2)
2. Net traction (P): Force in direction of travel developed by the traction device and transferred to the vehicle. (ASAE S296.2)
3. Motion resistance of traction device (R_2): the difference between gross traction and net traction. (ASAE S296.2)
4. Motion resistance of transport device (R_1): Energy required per unit distance of travel to overcome the resistance offered by the supporting surface and the internal resistance of the device. (ASAE S296.2)
5. Dynamic load (W): Total force normal to the plane of the undisturbed supporting surface, exerted by the traction or transport device under operating conditions. (ASAE S296.2)
6. Static load (W_s): Total force normal to the plane of the undisturbed supporting surface exerted by traction or transport device while stationary on level ground with zero net traction. (ASAE S296.2)
7. Slip (s): Relative movement in the direction of travel at the mutual contact surface of the traction or transport device and the supporting surface. (ASAE S296.2)
8. Zero conditions: Zero conditions may be those of zero net traction, or zero input torque for the traction

device as well as zero drawbar pull for the vehicle. (ASAE S296.2)

1.3.4 Engine terms

1. Rated speed (N_r): The speed in revolutions per minute specified by the tractor manufacturer for continuous operation at maximum power for a particular operation. (ASAE S209.5)
2. Specific fuel consumption: The ratio between the mass of fuel consumed per unit of time and corresponding measured power. (ASAE S209.5)

1.3.5 Tillage terms

1. Operating width (w): The horizontal distance performed by an implement, which is perpendicular to the direction of travel in one pass. (ASAE EP291.1)
2. Tillage depth (d): Vertical distance from the initial soil surface to a specified point of penetration of the tool. (ASAE EP291.1)
3. Primary tillage: Tillage which displaces and shatters soil to reduce soil strength, and to bury or mix plant materials and fertilizers in the tilled layer. Primary tillage is more aggressive, deeper, and leaves a rougher surface relative to secondary tillage. (ASAE S414)
4. Secondary tillage: Tillage that works the soil to a shallower depth than primary tillage, provides additional pulverization, levels and firms the soil,

closes air pockets, and kills weeds. Seedbed preparations are the final secondary tillage operations. (ASAE S414)

2. LITERATURE REVIEW

Of the three ways of transmitting tractor-engine power into useful work: power take off, hydraulic, and drawbar-the least efficient and most used method is the drawbar (Liljedahl et al., 1979).

To obtain the drawbar performance from a tractor, the tractor has to be operated on a certain medium which in agriculture is usually soil. Thus, to predict the tractor performance in fields, the investigation of both the tractor and the soil is necessary.

2.1 Studies of Soil Properties

2.1.1 Soil characteristics

In an engineering sense, soil is the relatively loose agglomerate of mineral and organic materials and sediments found above the bedrock, which is a heterogeneous, nonlinear, nonconservative, and anisotropic material. The soil is heterogeneous due to its variability, nonlinear due to the form of the stress-strain curve, nonconservative due to the ability to remember changes occurred in the past, and anisotropic due to differences in behavior along different directions. (Holtz and Kovacs, 1981)

In agricultural engineering the science of soil mechanics is applied to the design of tools, to the study of soil-vehicle interaction called terramechanics, and to the prediction of the performance of farming machinery. Compared

with forces occurring in soil mechanics problems in civil engineering, Koolen and Kuipers (1983) stated "the forces applied to soil in farming operations generally have a short duration, less than a few seconds, a small loaded area, of no more than a few square decimetres, and small intensities, 10 bar being the highest value. The soil properties vary widely between those of a weak mud and a stone-like dry soil."

Agricultural soils generally exhibit a degree of plastic behavior. The application of forces produces soil deformation or movement or both. (Gill and Vanden Berg, 1968) The reactions of soil to applied forces depend on the most relevant soil properties which are called strength properties. The soil of the surface region is compressible and the soil strength will increase as the soil compacts. (McKyes, 1985)

The textures of agricultural soil vary from sand to soils with a very high percentage of clay and/or organic content. The texture of soils combined with other factors like moisture content, soil management, etc. may greatly affect soil strength properties.

2.1.2 Coulomb's soil failure theory

In order to analyze the mechanism of soil failure, knowing under what regimes of force or pressure soil failure does occur is very important. The basis of soil mechanical strength knowledge is ascribed to Coulomb (1776) (McKyes,

1985). Working with masonry and soils, Coulomb noted that there appeared to be two mechanical processes in action which determine the ultimate shearing strength of both these materials. One process Coulomb called friction, and the other cohesion. In the first case, a portion of the shear strength is proportional to the pressure acting perpendicularly on the shearing surface. In the second case, part of the strength resisting shear movement is a constant regardless of the normal pressure. The total material shear strength is the sum of these two components as follows.

$$\tau_m = c + p \tan\phi \qquad (2.1)$$

where τ_m = the shear stress at failure, kPa.

c = cohesion of soil, kPa.

p = normal pressure on the shear surface, kPa.

ϕ = internal friction angle, degree.

c and ϕ are called the soil strength parameters. Coulomb's relationship gives a straight line as shown in Figure 2.1. In reference to equation (2.1), Gill and Vanden Berg (1968) stated the following:

> "While the straight line envelope of the Coulomb theory does not rigorously represent shear yield in all soil conditions, the theory has been close enough to experimentally observed behavior so that equation (2.1) has been almost universally accepted as a law. One confusing factor is that c and ϕ are so firmly entrenched that they are often referred to as real physical properties of the soil. In reality,

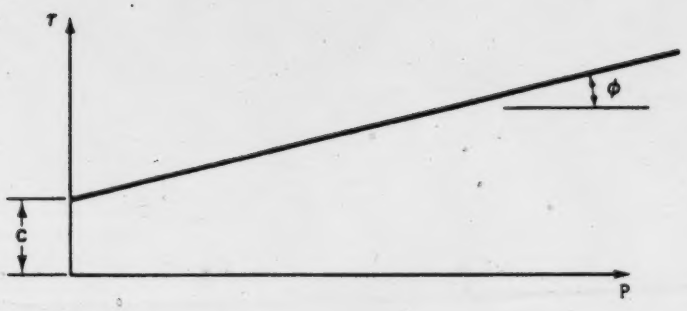


Figure 2.1 Coulomb's equation presented graphically (Adapted from Holtz and Kovacs, 1981)

they are only parameters of the assumed yield equation. Their logical existence can be explained only by an interpretation of the equation and not from the physical nature of the soil itself."

2.1.3 Measurement of soil strength properties

To evaluate the shearing strength of soils for calculation of the forces at the interaction between soil and tire, measured soil strength properties are required. Many apparatuses have been developed for measuring the strength properties of agricultural soil. Some are suitable for use only in the laboratory using a soil or block sample taken from the field and others only in the field. Therefore, soil measurements may be divided into two catagories: laboratory tests and *in situ* tests.

1. Laboratory tests

a. Direct shear test

The apparatus used in this test is a direct shear box composed of two or three metal rings having either a rectangular or circular opening as shown in Figure 2.2. A representative soil sample is placed in the opening of the ring and confined vertically by a force P. One of the rings is then moved horizontally with respect to the other one by means of horizontal force T. As T is increased, either continuously or by increments, the movement of the ring (δ) can be monitored, as can the vertical movement of the top confining plate (ΔH). At a sufficiently large value of the horizontal movement, the shear force ceases to increase at any appreciable rate, and it is deemed at that time that the soil shear strength has been developed fully, resulting in a maximum shear force. The test is repeated several times with different levels of the vertical force and the maximum shear force is determined at each test. A graph is then constructed of τ_m versus p and the c and ϕ values are obtained from the graph.

The advantages of the test are inexpensive costs, quick results, and simple equipment. The disadvantages are difficulty of controlling drainage, uncertainty of the failure plane, and serious stress concentrations at the boundaries (Holtz and Kovacs, 1981).

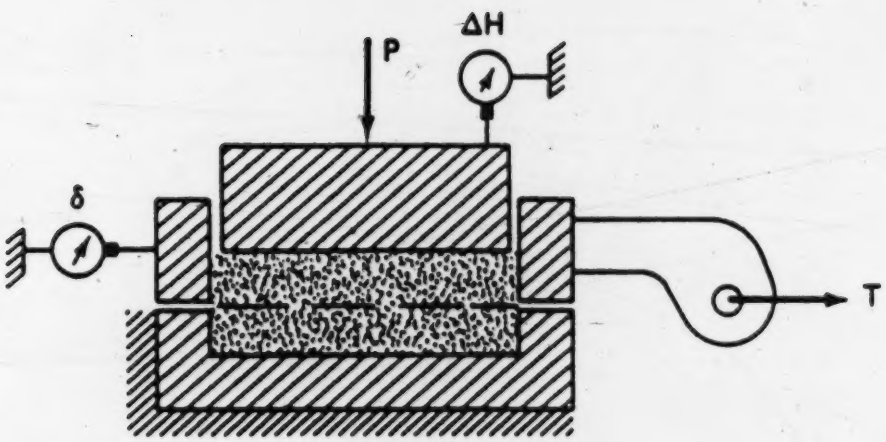


Figure 2.2 Cross-sectional schematic diagram of direct shear apparatus
(Adapted from Holtz and Kovacs, 1981)

b. Triaxial test

In the triaxial soil test, a sample of soil, usually cylindrical in shape, is confined by fluid, generally water, in a pressure-tight cell as shown in Figure 2.3. The pressure in the cell fluid (σ_c) is provided by an external source. A flexible rubber membrane surrounds the soil sample to prevent the cell fluid from penetrating the sample and altering its constitution. By means of a movable piston, a force P can be applied to the soil cylinder. The vertical displacement of the soil (ΔH) is monitored. The principal

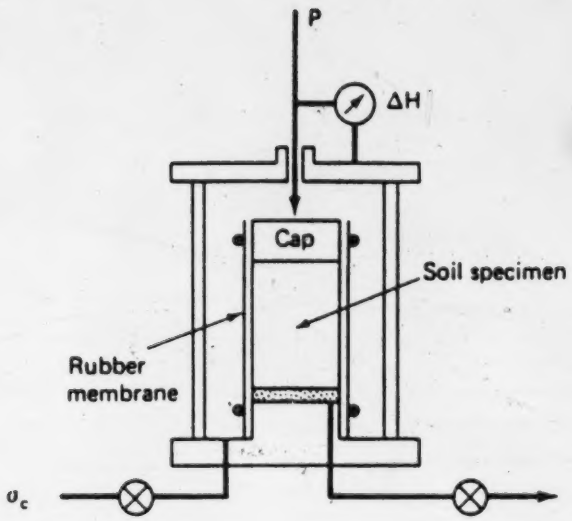


Figure 2.3 Schematic diagram of the triaxial apparatus (Adapted from Holtz and Kovacs, 1981)

stress on the sides of the sample is equal to the water pressure and the average stress acting vertically has a value of water pressure plus P/A where A is the cross sectional area of the soil cylinder and P is the normal force. To determine the strength parameters of a given soil, a series of shear tests is performed on the samples with different levels of cell fluid confining pressure. The major and minor principle stresses then are known for the soil failure condition and can be used to plot a Mohr's circle for each of the tests. The strength parameters, c and ϕ, are

determined from the envelope to these circles.

Other special laboratory tests may be listed as follows (Holtz and Kovacs, 1981):

- hollow cylindrical test
- plane strain test
- cuboidal shear test
- torsional or ring shear test

A major problem of the laboratory tests is that to obtain a sample and to prepare the sample for the test and mount the sample in the testing apparatus without changing the sample's strength properties is practically impossible. Thus, the strength properties obtained in the laboratory may not truly represent those on the site from which the sample was taken. The only solution to this problem appears to be a testing device that can be operated in the field and act directly on the soil.

2. *In situ* tests

a. Plate and annulus tests

The test is to measure soil cohesive and frictional strengths in one pass. The most often used apparatus are rectangular plate and annulus with grousers as shown in Figure 2.4. W is the load applied to the apparatus and D, b, l, h, r_o, and r_i are the dimensions of the apparatus. The rectangular or annulus plate is pressed against the soil surface and then moved linearly or rotated. The force or

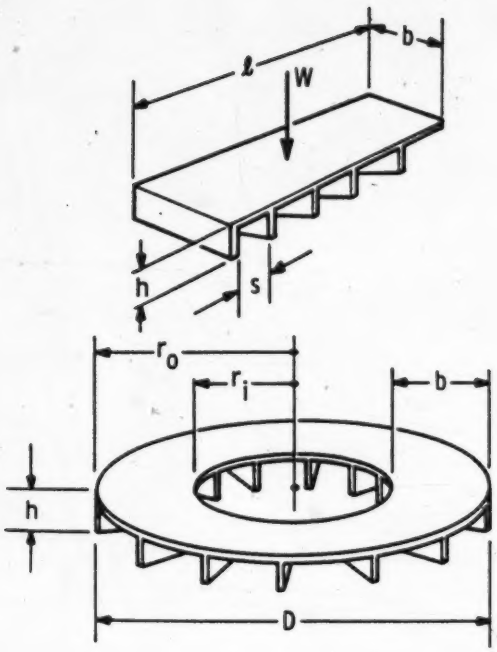


Figure 2.4 The shear apparatus--plate and annulus (Adapted from Bekker, 1969)

moment applied to the device and the soil deformation are recorded. To obtain the values of c and ϕ, a series of tests are needed with different levels of normal pressure. The idea of applying rectangular shear plates to locomotion studies was first described by Bekker in 1956. Although less favored than annulus plates, rectangular plates sometimes are used for testing high loads in situ, particularly if the performance of a heavy vehicle is to be measured in a strong soil (Bekker, 1969). For shear using an annulus, in the work reported by different authors, a great variety of ring

dimensions have been used. Bekker (1969) reviewed the dimensions used and indicated that the minimum size of a shear ring was determined by soil properties. Using rings with large dimensions is desirable because of the more uniform stress distribution under the annulus. In addition, large rings can reduce the grouser effect, i.e. the influence on the results due to the vertical side edges of the lugs where the normal stress are not controlled. The shear stress under an annulus can be calculated by using the following equation:

$$\tau = \frac{3M}{2\pi[(r_2)^3 - (r_1)^3]} \qquad (2.2)$$

where τ = shear stress under the plate, kPa.

M = moment applied on the annulus, kN-m.

r_1, r_2 = inner and outer diameters, m.

Volfson (1983) studied the soil strength measurement devices and claimed that soil cohesion varied with the different sizes of shear plate due to drag. Volfson also found that the measurements from the shear plate could best describe the interaction zone.

Wilkins et al. (1966) investigated the effect of geometrical shape of the devices on the measurements and reported that the three soil strength measuring devices: sheargraph, grouse annulus, and NIAE shear box did not give the same values of c and ϕ. Wilkins et al. also found that with different sizes of the grouser annuli in the same soil condition, the measurements were different. There has been no standard shear annulus for measuring soil strength to

date. However, the most often used annuli in agriculture have the ratio of outer diameter to inner diameter from 1.2 to 1.33.

b. Penetrometer test

The penetrometer and especially the cone penetrometer has gained wide-spread use among people concerned with soil mechanics probably because of its simplicity in use and construction.

The penetrometer does not distinguish between the cohesive and frictional components of soil strength. However, Janosi (1958) claimed that the cone index could be predicted by the land locomotion physical soil value for a given soil but that the reverse procedure of predicting the physical soil value from the cone index alone is not possible. Olsen (1978) found some correlation of the cone index to the product of cohesion and internal friction and pointed out that the penetrometer resistance is dependent on both strength parameters.

As a result, the penetrometer test only uses one number to represent soil strength. This number is called cone index: the force per unit base area of the cone required to push the penetrometer through a specified very small increment of soil.

Mulqueen et al. (1977) studied the value of the penetrometer in assessing the relative strength of soil and concluded that:

- the relative properties of shear, compressive and tensile strengths reflected by cone index varied with soil moisture content.
- as soil moisture content increased, the cone index became increasingly insensitive to shear strength or compressive strength changes.
- engagement of the shaft of the penetrometer by soil sometimes prevented attainment of the limit force as well as modifying the penetration force versus depth curve.

According to Freitag (1968), the factors that affect cone penetrometer measurements are the size of penetrometer shaft relative to cone size, the surface finish of the cone, the size and the shape of the cone, and the rate of penetration. The cone penetrometer test for agricultural purposes has been standardized by the ASAE as Standard S313.2 since 1978 to provide a standard uniform method of characterizing the penetration resistance of soils. In the standard, the means of measuring , describing, and reporting the composite soil resistance to penetration are discussed.

Other popular in situ tests are (McKyes, 1985):

- torsional shearhead
- sheargraph
- shear vane
- pocket penetrometer

The tests listed above are simple and fast. But the dimensions of the equipment used in these tests are quite

small. Therefore, the measurements may be more greatly affected by soil drag and heterogeneous characteristics of the soil than those in the annulus and penetrometer tests described above.

2.2 Studies of Tire and the Tire-Soil Interaction

2.2.1 Tire deflection

Calculation of tire deflection is very important in prediction of tractor performance since the tire deflection relates to the calculations of travel speed, axle torque, gross traction, and motion resistance. Knight and Green (1962) reported that the tire deflection, while traveling in a straight line, depended on the tire inflation pressure, tire carcass stiffness, load carried by tire, strength and type of surface on which the tire operates, and speed with which the tire moves.

Krick (1969) proposed a theoretical method to predict tire deflection on a rigid surface. The calculation is based on the assumption that the tire is a torus without deflection. The equation used is the following:

$$\delta = \frac{A}{\pi (Db')^{0.5}} \qquad (2.3)$$

where δ = tire deflection, m.

D = tire diameter, m.

b' = tire cross section equivalent diameter of curvature, m.

A = contact area, m^2.

The b' can be approximated by tire section width. The experimental work undertaken by Krick confirmed that the deflection calculated by equation (2.3) is in good agreement with measured data.

Yong et al. (1978) used the Finite Element Method to study tire deflection on a deformable surface. The input was the distribution of normal and shear stresses on the wheel-soil interaction. However, as Yong et al. stated, to get the stress distribution which will completely define the interaction is not easy. This is probably a limiting factor for the application of Finite Element Method to predicting tire deflection.

2.2.2 Stress distributions at tire-soil interface

The soil reaction forces are the resultant of the normal and shear stresses in the contact surface between wheel and soil. The stresses under a rigid wheel depend mainly on the size of the contact area. When the area of contact is small, stresses will be high. If the soil can not bear these high stresses without being deformed, the wheel sinks into the soil, increasing the size of the contact area until the required soil bearing capacity is attained. The essential difference between a rigid wheel and a wheel with a pneumatic tire is that a tire can deflect. In general, a tire moving on soft soil will involve tire deflection and sinkage in such a way that the tire deflecting force and soil sinkage reaction force balance each other.

For a towed smooth tire on soft soil, Vanden Berg and Gill (1962) investigated the case of a tractor pulling a test vehicle on a soft soil. Measured results showed that the maximum stress was ahead of the wheel axis.

For a driven smooth tire on soft soil, Krick (1969) found:

1. for the lateral direction, stresses near the side are higher with low slip.
2. for the travel direction:
   - stresses are lowest at the front and the rear of the contact surface and maximum stress occurs slightly ahead of the wheel axle.
   - only at high slip and in the middle of the track, does maximum stress occur at the front and the rear.
   - shear stresses are almost as great as normal stresses when slip is high.
   - the highest observed normal stress was lower than the inflation pressure.

For a driven tire with tread pattern on soft soil, Trabbic et al. (1959) reported that:

- as inflation pressure increased, the stresses in the center of the contact area increased, but stresses at the boundary decreased because the tire was deflected less and the slip increased.
- when drawbar pull increased, stresses on the loading lug face and between the lugs increased. Stresses under the lugs and at the trailing lug faces decreased.

Burt and Wood (1987) also reported that:

- maximum normal stress occurred at an angular position before maximum normal deflection.
- the ratio of normal stress to normal deflection was not constant across the tire width.
- maximum tangential stress occurred at an angular position before maximum tangential deformation.

2.2.3 Effects of bias-ply and radial-ply tires on traction

Radial-ply tractor drive tires were introduced in 1957 by the commercial application of an Italian tire manufacturing company (Forrest et al., 1962). Despite radial-ply tires being more expensive than the conventional bias-ply equivalents, research work has shown that radial-ply tires develop more drawbar pull and higher value of coefficient of traction for certain soil conditions than bias-ply tires. They have been gaining in popularity since they were introduced.

Thaden (1962) found that the radial-ply tire had greater deflection under load than its bias-ply equivalent, which resulted in an increase in contact area. The increase in contact area provided more flotation, less rolling resistance and soil compaction, and better traction performance.

Gee-Clough et al. (1977) evaluated radial-ply tires and concluded that the tractive performance increase obtained from using radial-ply rather than bias-ply drive tires in

British field conditions probably averaged 5-8% in the coefficient of traction at 20% slip with no change in maximum tractive efficiency, as long as the tires were not too highly inflated. As inflation pressure increased up to the maximum permissible value those benefits tended to disappear.

Hausz (1985) stated that the tractive advantages of radial-ply tires over bias-ply tires resulted from their deflection characteristics and pressure distribution. Radial-ply tires usually yielded a larger footprint than the same size bias-ply tire at the same load and inflation pressure. Even when the footprint of the radial-ply tire was not significantly greater than that of the bias-ply tire, test showed improved traction performance for the radial-ply tires. This was because the lugs on the radial-ply tires (near the center of the tread) had a much more uniform pressure distribution within the specific range of conditions.

2.2.4 Effects of dual tires on tractor performance

Dual tires can usually be obtained by rigidly attaching two identical tires together and spaced far enough apart to avoid interaction. The use of dual tires on large agricultural tractors is a common practice as farmers attempt to convert high engine power into drawbar power. Certainly for large tractors dual tire are necessary because a single tire may not have sufficient load carrying capacity

for the mass of the tractor and any additional ballast needed to develop high drawbar pulls.

Clark and Liljedahl (1969) reported on a soil bin study comparing single, dual, and tandem drive wheels. Small tires were tested in an artificial soil medium. They concluded that:

- the higher pressure dual tires were superior to the single tire only in the loose soil with slip less than 30%.
- in the medium firm and firm soil the high pressure dual tires provided slightly poorer performance than a single tire.
- dual tires did not improve the performance on the medium firm soil unless the inflation pressure of the dual tires was reduced below that of the single tire.

Domier and Friesen (1969) tested a number of tractors in the field and reported that under non-cohesive soil conditions single and dual wheel tractor performances had no significant difference at slippage in the normal working range. In wet clay, however, the dual wheel tractors increased traction by as much as 18%.

Melzer and Knight (1971) studied the influence of spacing between the dual wheels operating in sand. They found that dual wheel performance decreased as the relative wheel spacing increased. When wheel spacing was greater than a defined critical spacing which is usually 2 to 3.5 times the width of a single tire, the performance was that of the

single wheel.

Hutchings (1983) compared the performance between singles and duals and stated that the performance of dual and single tires had little difference when ballasted to the same level. However, where floatation was a problem, dual tires increased contact area resulting in less sinkage and rolling resistance.

Bashford et al. (1987) investigated performance of duals and singles on the rear axle of a front wheel assist tractor. They claimed that when the tractor was operated on a disked or plowed wheat stubble field or disked sandy soil, no significant difference in performance was detected when using dual or single drive tires on the rear axle. The results, however, imply that at slip much less than 15%, there is a slight advantage for the use of duals.

The field experiment conducted by Felsenstein et al. (1987) revealed that for a two wheel drive tractor in soft soil the tractive efficiency was higher for dual tires than for single tires. However, as the soil became firm, the reverse results were observed.

2.3 Traction Model

A traction model for a tractor usually has two essential components: the motion resistance of the driven and undriven wheels and the thrust of the driven wheels. Therefore, to complete a traction model, the motion resistance and the thrust for a tractor working in the field

must be formulated first.

2.3.1 Motion resistance

In order to develop more useful power by a tractor, the tractor designer would like to minimize the motion resistance. The components of motion resistance may be expressed as:

$$R = R_c + R_b + R_t \qquad (2.4)$$

where R = total motion resistance, kN.

R_c = resistance due to vertical soil compaction, kN.

R_b = resistance due to horizontal soil displacement, kN.

R_t = resistance due to tire flexing, kN.

The total motion resistance is, therefore, made up of the component due to vertical soil compaction, the component due to horizontal soil displacement, and the component due to tire flexing. For a tractor operating on a hard surface, R_t constitutes the largest percentage of the motion resistance force and can be slightly reduced by increasing the inflation pressure. In the field however, the components R_c and R_b make up the largest proportion of the motion resistance force and increasing inflation pressure and tire stiffness has been known to increase the motion resistance (McAllister, 1983).

A semi-empirical approach to predicting the force acting on wheels operating in soil was probably first initiated by Bernstein in 1913 (Plackett,1985). Bernstein's

theory stated that:

$$p = kZ^n \tag{2.5}$$

where p = pressure acting on the plate, kN.

k = soil constant, $\frac{kN}{m^n}$.

n = exponent of deformation.

Z = sinkage, m.

The theory is based on the observation that the motion resistance acting on a wheel was due to the work done in forming a rut, which can be represented by the pressure-sinkage characteristics of a rectangular plate.

Uffelmann (1961) investigated rigid wheels operating at small sinkage and suggested that:

$$p = 5.7c \tag{2.6}$$

where c is the cohesion of soil. Equation 2.6 is then used to compute motion resistance by calculating the sinkage necessary to support a wheel of diameter D. The motion resistance then becomes:

$$R = \frac{W^2}{5.7cbD} \tag{2.7}$$

where W = dynamic load on wheel, kN.

b = wheel width, m.

D = wheel diameter, m.

The equations have the advantage of being simple. The soil strength parameter of cohesion is used to characterize the soil, but the equations are only valid for a rigid wheel in clay soils. Bekker (1960, 1969) used the hypothesis stated by Bernstein to formulate a theory for predicting motion resistance force. Bekker proposed a pressure-sinkage

relationship of a rectangular plate in soil as follows:

$$p = (k_c + bk_\phi)\frac{z^n}{b} \tag{2.8}$$

where k_c = soil cohesion constant.

k_ϕ = soil frictional constant.

For a rigid wheel, the expression for the sinkage and compaction resistance component is:

$$R_c = \frac{1}{(n+1)(k_c+bk_\phi)^{1/(2n+1)}}\left(\frac{3W}{(3-n)d^{0.5}}\right)^{(2n+2)/(2n+1)} \tag{2.9}$$

For a pneumatic tire, if the ground pressure p is determined by:

$$p = p_i + p_t \tag{2.10}$$

where p_i = inflation pressure, kPa.

p_t = carcass stiffness, kPa.

the following equation is obtained for the sinkage and compaction resistance component of a pneumatic tire:

$$R_c = \frac{[b(p_i + p_t)]^{(n+1)/n}}{(n+1)(k_c+bk_\phi)^{1/n}} \tag{2.11}$$

To complete the calculation of motion resistance, Bekker also proposed expressions for bulldozing resistance and tire flexing. Reece (1966), Onafeko and Reece (1966), and Gee-Clough (1976) investigated and improved Bekker's theory.

The work described above has been based on a pressure-sinkage relationship. Freitag (1965), however, initiated a method based on dimensional analysis by which the motion resistance of pneumatic tires could be predicted.

The prediction technique developed by Freitag is based on two dimensionless mobility numbers as follows:

$$M = \frac{CIbD}{W}\left(\frac{\delta}{h}\right)^{0.5} \quad (2.12)$$

$$M_s = G(bD)^{1.5}\left(\frac{\delta}{h}\right) \quad (2.13)$$

where M = clay mobility number.

M_s = sand mobility number.

CI = cone index, kPa.

h = section height of the wheel, m.

δ = tire deflection, m.

G = gradient of cone index, $\frac{kPa}{m}$.

Freitag therefore used the cone index value and gradient of cone index to characterize the soil, and the parameters of load, tire width, diameter, section height, and deflection to characterize the wheel. Equations were then formed relating the coefficient of motion resistance to the mobility number.

Turnage (1972) undertook further work to improve the relationships proposed by Freitag and included an additional term to take the width/diameter ratio of the tire into account. Turnage's equation for the clay mobility number was:

$$M = \frac{CIbD}{W}\left(\frac{1}{1+b/2D}\right)\left(\frac{\delta}{h}\right)^{0.5} \quad (2.14)$$

Wismer and Luth (1973) used an approach similar to that used by Freitag to propose a wheel numeric C_n=CIbD/W which was related to motion resistance by:

$$C_r = \frac{1.2}{C_n} + 0.04 \quad (2.15)$$

where C_r is the coefficient of motion resistance and C_n is the wheel numeric.

An examination of mobility number methods was also undertaken by Dwyer et al. (1975) and later by Gee-Clough et al. (1978). This work led to the proposal of the expression:

$$C_r = \frac{0.287}{M} + 0.049 \qquad (2.16)$$

The mobility number (M) used was the clay number proposed by Turnage (Eqn 2.14). Experiments undertaken by Gee-Clough (1979) found the Freitag sand number to be of little use in agricultural soils.

McAllister (1983) also used the clay number of Turnage to propose improved relationships for the coefficient of motion resistance, including the effect of tire construction:

$$C_r = \frac{0.323}{M} + 0.054 \qquad (2.17)$$

for bias-ply tires, and

$$C_r = \frac{0.321}{M} + 0.037 \qquad (2.18)$$

for radial-ply tires.

Equations 2.17 and 2.18 were developed from experiments undertaken with wheels ranging from 0.8 m to 0.95 m in diameter, while Equation 2.16 was proposed working with wheels ranging from 1.45 m to 1.75 m in diameter. The difference between the equations demonstrate one of the problems of the mobility number method in that the mobility number method cannot be extrapolated with confidence.

2.3.2 Tractive force and complete models

The tractive force at the interaction between a driven wheel and soil is provided by the shear and the friction

reaction of soil. Therefore the magnitude of a tractive force is largely dependent on the ultimate strength of the soil.

Micklethwaite (1944) used Coulomb's equation (Eqn. 2.1) to predict the maximum possible tractive effort for a tracked vehicle. The equation developed was based on the assumption that the maximum sustainable shear stress of the soil multiplied by the contact area gave the maximum tractive force. The equation was expressed as the following form.

$$H_m = blc + W \tan\phi \qquad (2.19)$$

where H_m = maximum gross traction, kN.

b = contact width, m.

l = contact length, m.

W = dynamic load, kN.

Bekker (1960) examined Coulomb's equation and took the soil deformation into account. For a stress-deformation curve of the soil with a clear peak, Bekker proposed the following equation to fit the curve.

$$\tau = \frac{c + p \tan\phi}{Y_{mx}}\{EXP[-k_2 + (k_2^2-1)^{0.5}]\, k_1 sx - EXP[-k_2 - (k_2^2-1)^{0.5}]\, k_1 sx\} \qquad (2.20)$$

where k_1, k_2 = soil constants.

Y_{mx} = the maximum value of the term in brackets.

s = slip.

x = distance between the front end of ground contact area and the point where the unit soil thrust is to be determined, m.

The tractive force equation was then obtained by integrating the shear stress along the contact area.

$$H = \frac{2lb\,[c + p\tan(\phi)]}{k_1 s Y_{mx}}\left\{\frac{-1}{-k_2 + (k_2^2-1)^{0.5}} + \right.$$

$$\frac{EXP[-k_2 + (k_2^2-1)^{0.5}]\,k_1 sl}{-k_2 + (k_2^2-1)^{0.5}} + \frac{1}{-k_2 - (k_2^2-1)^{0.5}}$$

$$\left. - \frac{EXP[-k_2 + (k_2^2-1)^{0.5}]\,k_1 sl}{-k_2 - (k_2^2-1)^{0.5}}\right\} \qquad (2.21)$$

where H is the gross traction and l is the contact length.

Janosi and Hanamoto (1961) suggested the following equation for a stress-deformation curve without a clear peak.

$$\tau = (c + p\tan\phi)[1 - EXP(-\frac{sx}{K})] \qquad (2.22)$$

The gross traction could be obtained by integrating equation (2.22) along the interaction.

$$H = (blc + W\tan\phi)(1 + \frac{K}{sl}EXP(-\frac{sl}{K}) - \frac{K}{sl}) \qquad (2.23)$$

Janosi and Hanamoto also stated that using equation (2.23) for a stress-deformation curve with a clear peak would cause little effect on accuracy.

Equation 2.23 has been successfully used to predict tractive forces for a tracked vehicle (Plackett, 1985). Effort has also been made to use Equation 2.23 for a wheeled tractor. Dwyer et al. (1974) reported that soil shear strength was more closely related to coefficient of traction than cone index after examining equation 2.23 for a wheeled tractor.

Freitag, as mentioned previously, used dimensional analysis to produce two mobility numbers for a wheel-soil

system and Turnage improved the clay mobility number. Dwyer et al. (1975) used the mobility number of Turnage to examine experimental results obtained with agricultural tires. Gee-Clough (1979,1980) re-examined the work of Dwyer et al. using an empirical approach and proposed that:

$$C_{tmx} = 0.769 - \frac{0.92}{M} \quad (2.24)$$

$$C_t = C_{tmx}[1 - EXP(-ks)] \quad (2.25)$$

$$kC_{tmx} = 4.838 + \frac{0.92}{M} \quad (2.26)$$

where C_t = coefficient of net traction.

C_{tmx} = maximum coefficient of net traction.

k = rate constant.

M = clay mobility number.

s = wheel slip.

Zoz (1972) presented a graphical solution for predicting two-wheel drive tractor drawbar performance. The graph was based on average performance for single tires on concrete and three selected soil types. Zoz used three average weight transfer coefficients of 0.65 (integral), 0.45 (semi-integral), and 0.25 (towed) to determine the dynamic weight on the drive wheels since the method of attaching the load to the tractor will affect the tractor performance. To use the graph, the following parameters are required: the PTO power, type of soil, type of implement hitch, and no load travel speed.

Wismer and Luth (1973) developed traction equations for a tractor operating in the field. They defined a wheel numeric similar to Freitag's clay mobility number but for

constant values of $\delta/h = 0.20$ and $b/D = 0.3$.

$$C_n = \frac{CIbD}{W} \qquad (2.27)$$

where C_n = wheel numeric.

CI = cone index kPa, average value through to 150 mm.

W = dynamic wheel load, kN.

b = unloaded tire section width, m.

D = unloaded overall tire diameter, m.

For the driven wheel, they derived the gross traction as:

$$H = 0.75W[1 - EXP(-0.3C_n s)] \qquad (2.28)$$

where H is the gross traction and s is the wheel slip. Combined with the coefficient of motion resistance (Eqn. 2.15), the coefficient of traction for a wheel was obtained as following:

$$\frac{P}{W} = 0.75[1 - EXP(-0.3C_n s)] - (\frac{1.2}{C_n} + 0.04) \qquad (2.29)$$

where P is the wheel pull.

Macnab (1976) developed a computer model by using the Wismer and Luth equations. Macnab compared the predicted and tested data and reported that the equations were reasonably accurate except for vegetation surfaces. Clark (1985) modified the Wismer and Luth equations for vegetation surfaces and confirmed that the Wismer and Luth equations work well for short grass and bare surfaces with the average cone index value through the top 152 mm.

2.4 Fuel Consumption

Fuel efficiency varies by the type of fuel, percent load on the engine, and engine conditions.

Sulek and Lane (1968a, 1968b) used the Nebraska PTO varying power and fuel consumption data to derive fuel consumption equations for diesel, gasoline, and propane powered tractors. From their data analysis, they observed that gasoline and propane powered tractors showed a continuous increase in fuel economy as the load is increased. The fuel economy of diesel tractors peaked at 85% load and then dropped. They concluded that the maximum PTO power fuel economy of a tractor was a reasonably good indicator of the heavy load portion of the PTO varying load test. The variation in the light load fuel economy of all fuel classes could not be explained by variations in the maximum power fuel economy.

Persson (1969) developed an empirical relationship between fuel consumption and power. The equation for fuel consumption was:

$$F_h = \frac{1}{H_n \alpha}\left(3600P_p + \frac{cE_d N^2}{(2)(1.667\times10^{10})}\right) \qquad (2.30)$$

where F_h = fuel consumption, kg/h.

H_n = net heat value of fuel, mJ/kg.

N = engine speed, rpm.

E_d = engine displacement, cm^3.

P_p = engine power as measured at PTO shaft, kW.

2 = factor for four-stroke cycle engine.

α and c = engine constants determined from Nebraska Test data.

Macnab et al. (1977) used Persson's equations for their computer model which was validated by field test and they reported that the prediction was reasonably accurate.

Williams and Buck (1985) derived an empirical equation for fuel consumption at PTO loading below 50% of the rated maximum power and varied engine speed. The equation was validated by the field tests.

2.5 Draft of Implements

The draft of implements depends on the type and width of implement, soil, and tillage depth. Kydd et al. (1984) conducted field tests over a wide range of soil in the Prairie provinces for determination of draft in tillage operation. They developed a number of draft equations for various implements and concluded that draft depends mainly on tillage depth.

Summers et al. (1986) studied draft relationships for primary tillage in Oklahoma soils and concluded that:

- draft is linear with speed for chisel plows, disks, and sweep plows and is quadratic with speed for moldboard plows.
- draft is linear with depth for moldboard plows, chisel plows, disks, and sweep plows.

3. MODEL DEVELOPMENT

The complete model for predicting tractor performance in the field consists of three main parts. The first part models tractive performance. The second part predicts the fuel consumption. The last part deals with the tractor-implement performance in tillage operation. The model was developed with the following assumptions.

1. Soil conditions are homogeneous and soil strength can be described by cone index or shear strength parameters.
2. Both sides of a driving axle have equal slip.
3. Tractor weight is equally distributed between the left and right sides.
4. For four wheel drive or front wheel assist tractor, the front wheel slip and the rear wheel slip are equal.
5. The tractor is operating on level ground.
6. The load applied at the drawbar is horizontal and parallel to the drawbar.
7. The motion resistances and the thrusts of the front and rear wheels are in the same horizontal plane.
8. The effects of sinkage on the drawbar height is negligible.
9. The tractor operates at constant speed in the field.
10. The contact pressure between wheel and soil is assumed to be uniformly distributed and approximately the sum of the inflation pressure and the carcass stiffness.

For the tractive model based on cone index, the

following two assumptions are needed.

11. The ratio of unloaded tire section width to unloaded overall tire diameter is approximately 0.30.
12. The ratio of tire deflection to tire section height is approximately 0.20.

For the tractive model based on shear strength parameters, one additional assumption is added.

13. The thrust of a driving wheel is generated by shearing the soil over the contact area.

3.1 Tractive Performance

3.1.1 Motion resistance and thrust

The tractive model involves the physical characteristics of the tractor, the drawbar load, and the soil conditions. The most important part of this model is the calculation of the motion resistance of the tractor and the thrusts of the driving wheels since the motion resistance and the thrusts relate to tire and soil characteristics. Two approaches are presented in this study to calculate traction forces. One is based on soil cone index and the other is based on soil cone index for motion resistance and soil shear parameters for thrusts.

a. Approach I

The Wismer and Luth equations for single pneumatic tires operation on soils are the basis for this approach. The equations predict the forces acting on both towed and

driving wheels. The towed force of a wheel is predicted from:

$$\frac{TF}{W} = \frac{1.2}{C_n} + 0.04 \qquad (3.1)$$

where TF = towed force, kN.

W = dynamic load on wheel, kN.

C_n = wheel numeric defined by equation 2.27.

The motion resistance of an axle of the tractor with single tires can be approximated by the sum of the towed forces for the wheels on the axle. The motion resistance of axles of a tractor with single tires is:

for the front axle:

$$R_1 = W_{d1}(\frac{1.2}{C_{n1}} + 0.04) \qquad (3.2)$$

for the rear axle:

$$R_2 = W_{d2}(\frac{1.2}{C_{n2}} + 0.04) \qquad (3.3)$$

where R_1, R_2 = motion resistance of front and rear axles respectively, kN.

W_{d1}, W_{d2} = dynamic load of front and rear axles respectively, kN.

C_{n1}, C_{n2} = front and rear wheel numeric respectively.

The wheel numeric for a tractor with single tires is defined as:

$$C_n = \frac{2CIbD}{W_d} \qquad (3.4)$$

where CI = soil cone index, kPa.

W_d = dynamic axle load, kN.

Wismer and Luth defined the cone index in equation 3.4 as the average cone index in the 0-150 mm depth.

Similarly, the driving wheels of a two wheel drive or four wheel drive tractor with single tires are modeled by the Wismer and Luth equation as:

$$\frac{P}{W} = 0.75[1 - EXP(-0.3C_n s)] - (\frac{1.2}{C_n} + 0.04) \quad (3.5)$$

where P = net pull of the wheel, kN.

s = wheel slip.

W = dynamic wheel load, kN.

C_n = wheel numeric.

This equation is limited to tires with the ratio of unloaded section width to unloaded overall diameter of approximately 0.3 and the ratio of tire deflection to tire section height of approximately 0.2. The equation has two components. The first is the thrust developed by the wheel and the second is the motion resistance of the wheel. The subtraction of motion resistance from thrust yields net pull of the wheel.

For a tractor with single tires, equation 3.4 is applied directly. The thrust of a powered axle is then determined by the sum of the thrusts of the driving wheels. The equations are written as:

for the front axle:

$$H_1 = 0.75\ W_{d1}[1 - EXP(-0.3C_{n1}s_1)] \quad (3.6)$$

for the rear axle:

$$H_2 = 0.75\ W_{d2}[1 - EXP(-0.3C_{n2}s_2] \quad (3.7)$$

where H_1, H_2 = front, rear axle thrust, kN.

W_{d1}, W_{d2} = front, rear dynamic axle load, kN.

s_1, s_2 = front, rear wheel slip.

C_{n1}, C_{n2} = front, rear wheel numeric.

The Wismer and Luth equations were derived from test results with single tires. To apply those equations to dual tires, certain changes must be made. The simplest method is to treat duals as two singles with half the dynamic load on each and then apply Wismer and Luth equations to each tire. This treatment, however, usually results in an over-estimate of dual tire performance with conventional dual tire spacing except in soft soils (Clark and Liljedahl, 1969). Several traction researchers (Clark and Liljedahl, 1969, Melzer and Knight, 1971, and Felsenstein et al. 1987) have revealed that when the soil is soft, dual tires are superior to single tires because of less motion resistance. However, as the soil become firmer, the advantages of dual tires tend to disappear. Based on this observation, an equivalent width ratio is introduced in order to use Wismer and Luth equations for dual tires.

The equivalent width ratio defined as the ratio of equivalent width of dual tires to single tire width, is assumed to be a function of soil cone index. When the soil is soft, the dual tire performance is calculated by adding the performance of the two single tires of the dual pair. When the soil is firm, the dual tire performance is just like one single tire of the dual pair. A linear relationship between the equivalent width ratio and cone index was observed between soft and firm soil from the field test results in the Fuel Usage Demonstration project conducted by Alberta Agriculture and Olds College. The relationship

between soft and firm soil may be described as:

$$b_e = a_0 + a_1 CI \qquad (3.8)$$

where b_e = equivalent width ratio.

a_0, a_1 = constants.

CI = cone index, kPa.

For 20.8(R)38 dual tires, the constant a_0 and a_1 are 2.67 and -0.0015 between cone index values of 446 kPa and 1113 kPa. The constants may be different for other tires. The relationship between equivalent width ratio and cone index for 20.8(R)38 dual tires is shown in Figure 3.1. The test data in figure 3.1 are the average equivalent width ratios with which the field test data are best fitted by Wismer and Luth equations.

Substituting equivalent width for tire width in wheel numeric yields:

$$C_{nd} = \frac{4CIbD}{W_d} \text{ for soft soil,}$$

$$C_{nd} = \frac{2CIbD}{W_d} \text{ for firm soil, and}$$

$$C_{nd} = \frac{2CIbD(a_0 + a_1 CI)}{W_d} \text{ between soft and firm soil} \qquad (3.9)$$

where W_d = dynamic axle load, kN.

C_{nd} = dual wheel numeric.

Wismer and Luth equations are then applied to dual tires for towed and driving wheels with the wheel numeric in equation 3.9. In fact, the introduction of the equivalent width ratio for dual tires results in a change in the calculation of the motion resistance and the thrust. In soft soil, dual tires will reduce the motion resistance compared with single tires. In firm soil, however, dual tires have

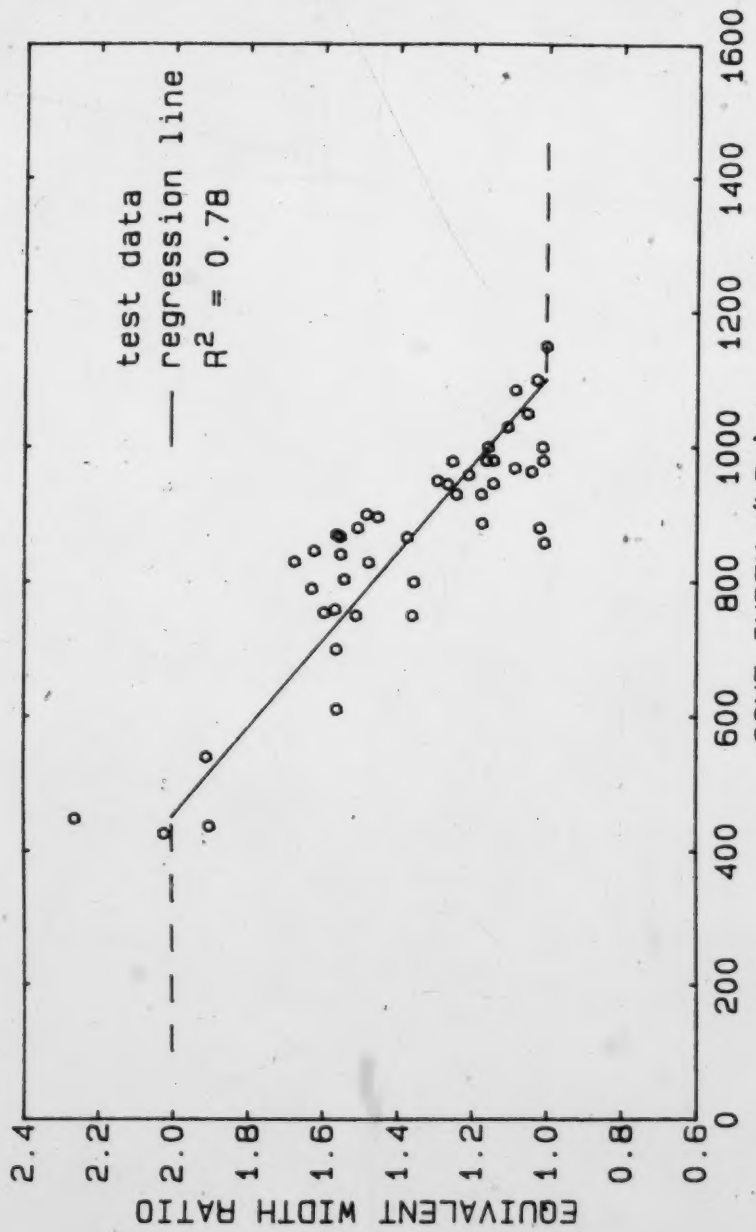


Figure 3.1 Relationship between equivalent width ratio and cone index for 20.8(R)38 dual tires.

the same motion resistance as singles (Friesen and Domier, 1968).

b. Approach II

In this approach, the prediction of thrusts are calculated based on Bekker theory. The motion resistance, however, is calculated in the same way as the first approach since Dwyer et al. (1975) pointed out that the correlation of plate sinkage measurement with motion resistance of wheels was very poor.

For a single wheel, the thrust is calculated from:

$$H = (Ac + W\tan\phi)[1 + \frac{K}{sl}EXP(\frac{-sl}{K}) - \frac{K}{sl}] \quad (3.10)$$

where H = thrust, kN.

A = contact area between wheel and soil, m^2.

W = dynamic load on wheel, kN.

c = cohesion of the soil, kPa.

ϕ = internal friction angle of the soil, deg.

K = soil deformation modulus, m.

l = contact length, m.

The above equation is based on the assumption that the thrust results from the shearing of soil over the contact area and that the normal pressure over the contact area is uniformly distributed. Obviously, equation 3.9 does not take the slip due to tire deformation into account. Dwyer et al. (1974) found that slip due to tire deformation for a single tire was a function of coefficient of gross traction. They suggested the following relationship for agricultural tires.

$$s_d = 0.16C_{gt} \quad (3.11)$$

where s_d is the slip due to tire deformation and C_{gt} is the coefficient of gross traction.

Adding the slip due to tire deformation to the slip in equation 3.10 gives:

$$H = (Ac + W\tan\phi)[1 + \frac{K}{(s+s_d)l}EXP(\frac{-sl-s_dl}{K}) - \frac{K}{(s+s_d)l}] \quad (3.12)$$

For the tractor with single tires, equation 3.12 is applied to calculate the thrusts of driving wheels. The thrusts then become:

for front wheel drive:

$$H_1 = (A_1c + W_{d1}\tan\phi)[1 + \frac{K}{(s_1+s_{d1})l_1}EXP(\frac{-s_1l-s_{d1}l_1}{K}) - \frac{K}{(s_1+s_{d1})l_1}] \quad (3.13)$$

for rear wheel drive:

$$H_2 = (A_2c + W_{d2}\tan\phi)[1 + \frac{K}{(s_2+s_{d2})l_2}EXP(\frac{-s_2l-s_{d2}l_2}{K}) - \frac{K}{(s_2+s_{d2})l_2}] \quad (3.14)$$

where H_1, H_2 = front or rear axle thrust, kN.

A_1, A_2 = front or rear axle contact area, m^2.

s_1, s_2 = front or rear wheel slip.

s_{d1}, s_{d2} = front or rear slip due to tire deformation.

l_1, l_2 = contact length, m.

The slip due to tire deformation is likely smaller for a tractor with dual tires. From the field test data, s_d is almost a constant of 0.015 for dual tires. Substituting s_{d1} and s_{d2} in equation 3.12 and 3.13 for 0.015, equation 3.12 and 3.13 are used to calculate the thrusts of the driving wheels with dual tires.

3.1.2 Tractive model completion

The equations for motion resistances and thrusts have been described in Approach I and Approach II. However, the dynamic loads on axles in the equations are unknown. More equations are needed for the dynamic axle loads and the drawbar pull. From the force and moment equilibrium of a tractor, a group of equations can be established and the dynamic axle loads and the drawbar pull can be obtained by solving the group equations. The free body diagram of a tractor is shown in Figure 3.2 for a two wheel drive tractor and Figure 3.3 for a four wheel drive tractor. The number of degrees of freedom of the diagram is three. Therefore, three independent equations can be written from the diagram.

Taking the moments about the point at the interaction between the rear wheel and the surface directly under the rear axle yields:

$$W_{d1} = \frac{1}{L+m_1}(W_{s1}L - W_{d2}m_2 - F_d h) \qquad (3.15)$$

where W_{d1} = dynamic load of the front axle, kN.

L = wheelbase of the tractor, m.

W_{s1} = static weight of the front axle, kN.

m_1, m_2 = front, rear motion resistance arm, m.

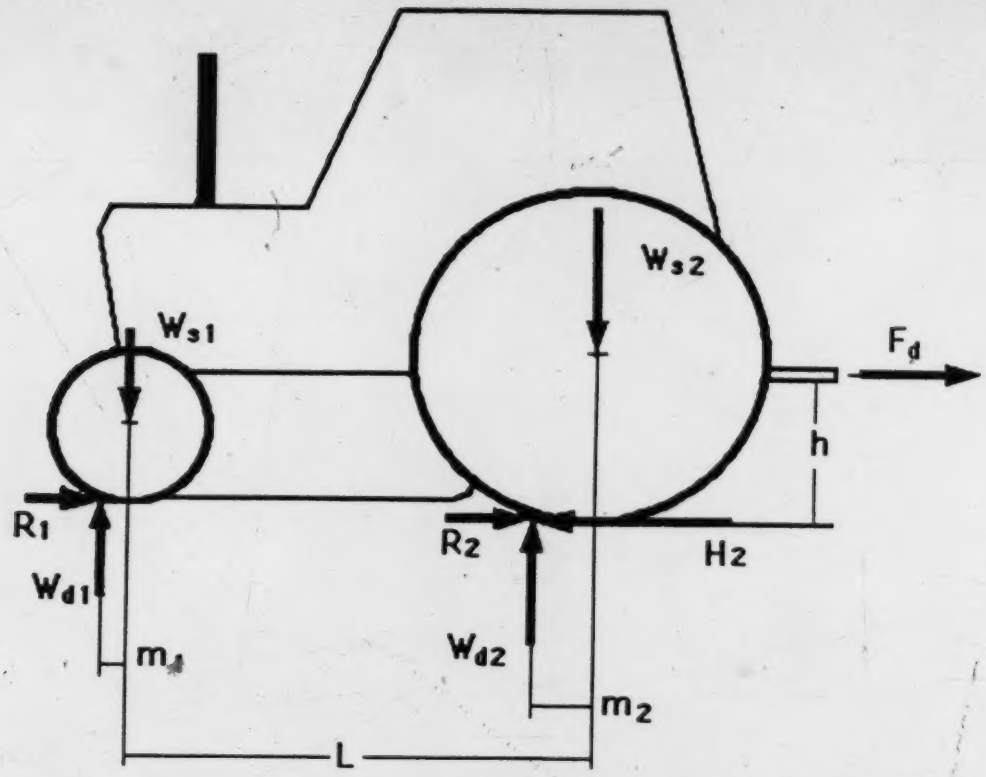
F_d = drawbar pull, kN.

h = drawbar height, m.

Similarly, taking the moments about the point at the interaction directly under the front axle gives:

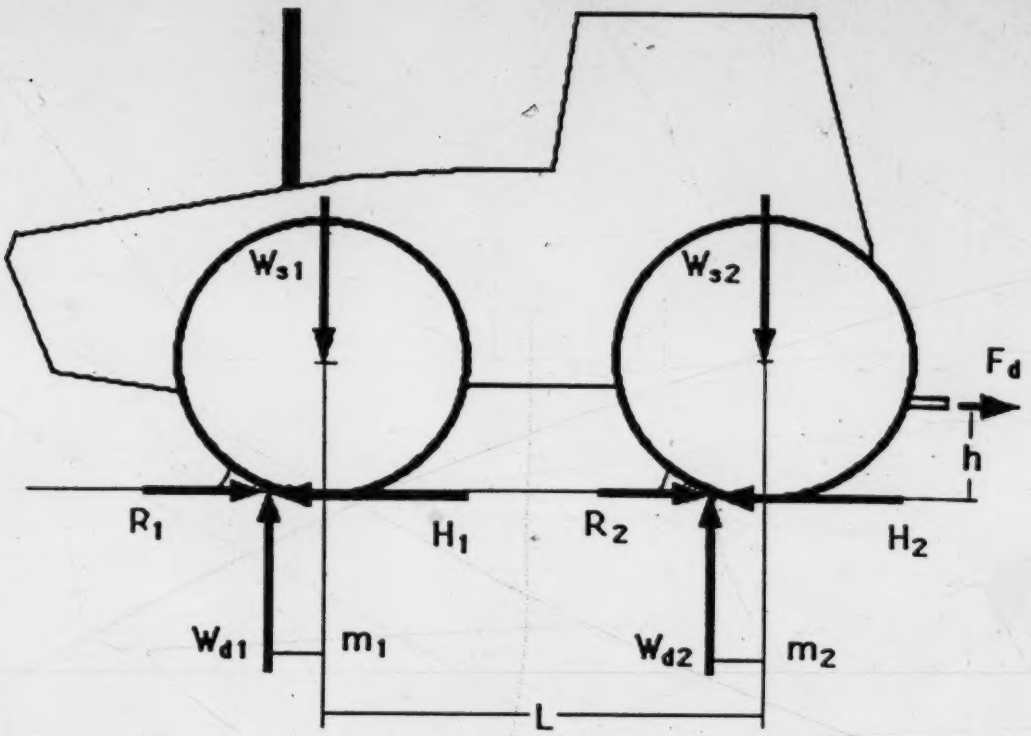
$$W_{d2} = \frac{1}{L-m_2}(W_{s2}L + W_{d1}m_1 + F_d h) \qquad (3.16)$$

where W_{d2} is the dynamic rear axle load and W_{s2} is the



W_{s1} = Front Static Axle Load
W_{s2} = Rear Static Axle Load
W_{d1} = Front Dynamic Axle Load
W_{d2} = Rear Dynamic Axle Load
H_2 = Rear Wheel Thrust
R_1 = Front Wheel Motion Resistance
R_2 = Rear Wheel Motion Resistance
F_d = Drawbar Pull
L = Wheelbase
h = Drawbar Height
m_1 = Front Wheel Motion Resistance Arm
m_2 = Rear Wheel Motion Resistance Arm

Figure 3.2 Forces acting on a two wheel drive tractor



W_{s1} = Front Static Axle Load.
W_{s2} = Rear Static Axle Load
W_{d1} = Front Dynamic Axle Load
W_{d2} = Rear Dynamic Axle Load
H_1 = Front Wheel Thrust
H_2 = Rear Wheel Thrust
R_1 = Front Wheel Motion Resistance
R_2 = Rear Wheel Motion Resistance
F_d = Drawbar Pull
L = Wheelbase
h = Drawbar Height
m_1 = Front Wheel Motion Resistance Arm
m_2 = Rear Wheel Motion Resistance Arm

Figure 3.3 Forces acting on a four wheel drive tractor

static rear axle load of the tractor.

Summing the horizontal direction forces of a two wheel drive tractor gives the drawbar pull as:

$$F_d = H_2 - R_1 - R_2 \qquad (3.17)$$

For a four wheel drive tractor, the drawbar pull is:

$$F_d = H_1 + H_2 - R_1 - R_2 \qquad (3.18)$$

The equations for H_1, H_2, R_1, and R_2 have been described previously. The motion resistance arms in equations 3.15 and 3.16, however, are still unknown. Therefore, two more equations are required to describe the motion resistance arms.

The motion resistance arm of a driving wheel is assumed to be the same as that of a towed wheel. The forces acting on a towed wheel are shown in Figure 3.4. The motion resistance arm is:

$$m = \frac{r_d R}{W} \qquad (3.19)$$

where m = motion resistance arm, m.

R = motion resistance, kN.

W = dynamic wheel load, kN.

r_d = effective radius of the wheel, m.

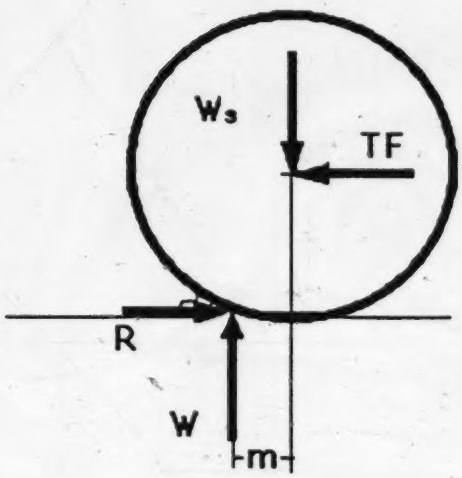
The effective radius of a wheel, according to Charles (1984), is defined as:

$$r_d = (1 - k)r_n + kr \qquad (3.20)$$

where r_d = effective radius, m.

k = constant, for radial ply tire k = 0.4, for bias ply tire k = 0.63.

r_n = unloaded tire radius, m.



W_s = Static Wheel Load

W = Dynamic Wheel Load

R = Motion Resistance

m = Motion Resistance Arm

TF = Towed force

Figure 3.4 Forces acting on a towed wheel

r = loaded tire radius, m.

The loaded tire radius in equation 3.20 is the loaded radius on a hard surface which is obtained by subtracting the tire deflection from the unloaded tire radius. Rewriting equation 3.20 gives:

$$r_d = kr_n + k\delta \tag{3.21}$$

where δ as determined by equation 2.3 is the tire deflection on a hard surface.

Combining equation 3.19 and 3.21 yields:

$$m = \frac{(kr_n + k\delta)R}{W} \tag{3.22}$$

For front wheels of a two wheel drive tractor, the tire deflection is neglected and the motion resistance arm is:

$$m_1 = \frac{kr_{n1}R_1}{W_{d1}} \tag{3.23}$$

For front driving wheels, the motion resistance arm is written as:

$$m_1 = \frac{(kr_{n1} + k\delta_1)R_1}{W_{d1}} \tag{3.24}$$

The motion resistance arm for rear driving wheels is expressed as:

$$m_2 = \frac{(kr_{n2} + k\delta_2)R_2}{W_{d2}} \tag{3.25}$$

where r_{n1}, r_{n2} are the front and rear unloaded tire radii and δ_1, δ_2 are the front and rear tire deflections.

The group equations for determining the motion resistance, the thrusts, the dynamic axle loads, and the drawbar pull have been completed. The group equations for Approach I for a two wheel drive tractor involves equations 3.2, 3.3, 3.4, 3.7, 3.15, 3.16, 3.17, 3.23, and 3.25 for single tires and equations 3.2, 3.3, 3.7, 3.9, 3.15, 3.16,

3.17, 3.23, and 3.25 for dual tires. For a four wheel drive tractor, equations 3.2, 3.3, 3.4, 3.6, 3.7, 3.15, 3.16, 3.18, 3.24, and 3.25 are used for single tires and equations 3.2, 3.3, 3.6, 3.7, 3.9, 3.15, 3.16, 3.18, 3.24, and 3.25 are used for dual tires.

The group equations for Approach II for a two wheel drive tractor includes equations 3.2, 3.3, 3.4, 3.14, 3.15, 3.16, 3.17, 3.23, and 3.25 for single tires and equations 3.2, 3.3, 3.9, 3.14, 3.15, 3.16, 3.17, 3.23, and 3.25 for dual tires. For a four wheel drive tractor equations 3.2, 3.3, 3.4, 3.13, 3.14, 3.15, 3.16, 3.18, 3.24, and 3.25 are used for single tires and equations 3.2, 3.3, 3.9, 3.13, 3.14, 3.15, 3.16, 3.18, 3.24, and 3.25 are used for dual tires. If the static loads on the tractor, dimensions of the wheels, and the soil properties are defined, for a given slip, the number of unknown variables in the group equations is equal to the number of equations. Therefore, the forces acting on a tractor working in the field are defined by the group equations.

Once the drawbar pull and the dynamic axle loads are known, other tractive performance parameters are calculated for the tractive model.

The torque of a driving axle is defined as the axle thrust acting through an effective radius of the driving wheels. The driving axle torque is expressed as:

$$Q = Hr_d \tag{3.26}$$

where Q = axle torque, kN-m.

H = axle thrust, kN.

r_d = effective radius, m.

For a two wheel drive tractor, the total axle torque (Q_2) is:

$$Q_2 = H_2 r_{d2} \text{ , kN-m} \tag{3.27}$$

For a four wheel drive or front wheel assist tractor, the total axle torque (Q_4) is written as:

$$Q_4 = H_1 r_{d1} + H_2 r_{d2} \text{ , kN-m} \tag{3.28}$$

where r_{d1} and r_{d2} are the front and rear effective radii.

According to Zoz (1972), the transmission efficiency from engine crankshaft to axle is approximately 0.82. The torque developed by the engine is:

$$Q_e = \frac{Q_2}{0.82 G_n} \text{ , kN-m} \tag{3.29}$$

for a two wheel drive tractor or

$$Q_e = \frac{Q_4}{0.82 G_n} \text{ , kN-m} \tag{3.30}$$

for a four wheel drive tractor, where G_n is the gear ratio between engine crankshaft and axle.

The engine speed is then obtained from the torque-speed curve of the engine. The theoretical travel speed (zero slip travel speed) V_t is calculated by the following equation.

$$V_t = \frac{7.2\pi r_d N}{60 G_n} \text{ , km/h} \tag{3.31}$$

where N is the engine speed, rpm.

The slip is defined as:

$$s = 1 - \frac{V_d}{V_t} \tag{3.32}$$

where s = wheel slip.

V_d = actual travel speed, km/h.

V_t = theoretical travel speed, km/h.

The actual travel speed is then determined by equation 3.32 when the slip is given.

The zero slip condition in the study is defined as a self-propelled operation on a hard surface with no drawbar load. For the tractive model, all driving wheels on a axle are assumed to have the same slip.

The drawbar power P_d is the product of the drawbar pull and the actual travel speed. which is written as:

$$P_d = \frac{V_d F_d}{3.6} \text{ , kW} \qquad (3.33)$$

where V_d is the actual travel speed in km/h.

Similarly, the axle power is the product of the axle torque and the angular speed of the axle. The axle power is described as:

for a two wheel drive tractor

$$P_a = \frac{Q_2 V_t}{3.6 r_{d2}} \text{ , kW} \qquad (3.34)$$

for a four wheel drive tractor

$$P_a = \left(\frac{Q_{d1}}{3.6 r_{d1}} + \frac{Q_{d2}}{3.6 r_{d2}}\right) V_t \text{ , kW} \qquad (3.35)$$

where Q_{d1} and Q_{d2} are the front and rear axle torques.

The PTO power is, from Zoz (1972), approximately the axle power divided by 0.96.

The tractive efficiency of a tractor is defined as the ratio of drawbar power to axle power. For a two wheel drive tractor, the tractive efficiency (T_{e2}) is:

$$T_{e2} = \frac{r_{d2} F_d}{Q_2}(1 - s) \qquad (3.36)$$

If the front wheel slip and the rear wheel slip are assumed the same, the tractive efficiency for a four wheel drive tractor can be expressed as:

$$T_{e4} = \frac{F_d}{H_1+H_2}(1 - s) \qquad (3.37)$$

where T_{e4} = tractive efficiency of a four wheel drive tractor.

H_1, H_2 = front, rear axle thrust, kN.

F_d = drawbar pull, kN.

3.2 Fuel Consumption Model

The fuel consumption of a tractor relates to the engine characteristics, the load of the tractor, and the efficiency at which the tractor converts rotary energy into linear energy. Some of the engine parameters important in predicting fuel consumption are engine speed, engine displacement, thermal and mechanical efficiency and power output. The empirical relationships of part load and varying speed fuel consumption of a tractor derived by Persson (1969) are the foundation for the model. Part load and varying speed fuel consumption of a tractor can be expressed as:

$$F_h = \frac{1}{H_n \alpha}\left(3600P_p + \frac{cE_d N^2}{(2)(1.667 \times 10^{10})}\right) \qquad (3.38)$$

where F_h = fuel consumption, kg/h.

H_n = net heat value of fuel, mJ/kg.

N = engine speed, rpm.

E_d = engine displacement, cm^3.

P_p = engine power as measured at PTO shaft, kW.

2 = factor for four-stroke cycle engine.

α and c = engine constants.

Persson using data from the Nebraska Varying Power and Fuel Consumption Tests showed that a nearly linear relationship existed between PTO mean effective pressure (Pmep) and the fuel consumption term (β). The equation for the straight line is:

$$\beta = \frac{1}{a}(Pmep + b) \qquad (3.39)$$

where β = fuel consumption term, kJ/m^3.

Pmep = PTO mean effective pressure, kPa.

b = constant, kPa.

a = the inverse of the slope of the line, $\frac{kN\text{-}m}{kJ}$.

The relationship between fuel consumption term (β) and fuel consumption is expressed as:

$$\beta = \frac{(2)H}{NE_d} F_h \qquad (3.40)$$

and the PTO mean effective pressure is calculated from the following equation.

$$Pmep = \frac{120x10^4}{E_d N} P_p \qquad (3.41)$$

Persson found that the points between the 85 and 21.3 percent load points were on or very close to the straight line. Therefore, Persson suggested the 85 and 21.3 percent load points be used to determine the line of equation 3.39. Macnab (1976) utilized regression analysis of fuel consumption term (β) versus PTO mean effective pressure (Pmep) for ten individual Nebraska Tractor Tests and confirmed that the 85 and 21.3 percent load points fell extremely close to the regression line and that the 100 percent load point was above the regression line.

The coefficients of a and b in equation 3.39 can then be determined by using the 85 and 21.3 percent load points. Substituting the values of β and Pmep at 85 and 21.3 percent loads into equation 3.39 yields:

$$\beta_{85} = \frac{1}{a}(Pmep_{85} + b) \tag{3.42}$$

and

$$\beta_{21.3} = \frac{1}{a}(Pmep_{21.3} + b) \tag{3.43}$$

where β_{85} and $\beta_{21.3}$ = the β values at 85 and 21.3 percent load, kJ/m^3.

$Pmep_{85}$ and $Pmep_{21.3}$ = PTO mean effective pressures at 85 and 21.3 percent loads, kPa.

The fuel consumption terms β_{85}, $\beta_{21.3}$ and the PTO mean effective pressures $Pmep_{85}$, $Pmep_{21.3}$ are calculated by equations 3.40 and 3.41.

Combining equations 3.42 and 3.43 gives equations for coefficients a and b as follows:

$$a = \frac{Pmep_{85} - Pmep_{21.3}}{\beta_{85} - \beta_{21.3}} \tag{3.44}$$

and

$$b = \beta_{85}a - Pmep_{85} \tag{3.45}$$

In the Nebraska Tractor Tests, all of the fuel consumption tests except one are conducted at full throttle. Therefore, to use Nebraska Test data to determine the effect of reduced engine speed on fuel consumption was not possible. Persson used data from Swedish and German tractor test reports and discovered that the coefficient b varied with engine speed. The equation describing this variation was:

$$b = \frac{cN}{1000} \tag{3.46}$$

where c = coefficient in equation 3.38, kPa/1000rpm.

N = engine speed, rpm.

Rearrangement of equation 3.46 yields:

$$c = \frac{1000b}{N} \tag{3.47}$$

According to Persson, the relationship between coefficient α and coefficient a is:

$$a = \alpha J \tag{3.48}$$

where J = mechanical heat equivalent, $J=1\ \frac{kN-m}{kJ}$.

Substituting equation 3.46 for b and α for a into equation 3.39 yields the following equation.

$$\beta = \frac{1}{\alpha}(Pmep + \frac{cN}{1000}) \tag{3.48}$$

Combining equations 3.40 and 3.48 and replacing Pmep with equation 3.41 gives Persson's fuel consumption equation at part load and varying speed as expressed in equation 3.38. The PTO power in equation 3.38 for a tractor working in field is determined from the tractive model described previously.

3.3 Tractor-Implement Combination Model

To predict tractor performance in tillage operation, it is necessary to examine the tractor-implement combination since the draft of the implement in most situations varies with type of machine, tillage depth, width, field speed and field conditions. To obtain general equations which could closely model the draft requirement of different types of implements in various field conditions is very difficult

since the draft of an implement is affected by a number of factors and may vary a lot from one area to another. Therefore, the tractor-implement combination model in this study is limited to towed implements commonly used in the Prairie Provinces of Canada. The model can be divided into two parts. The first part deals with the draft requirement of an implement. The second part predicts the tractor performance including the fuel consumption. The tractive performance and fuel consumption models have been described previously. The draft prediction of an implement, therefore, is focused in this section.

The draft equations of implements for Western Canada derived by Kydd et al. (1984) are the basis of this part of the model. Kydd et al. used the draft requirement data collected in a wide range of soils and field conditions typical of the Prairie Provinces by the Prairie Agricultural Machinery Institute to present a number of average draft equations for different machine types.

In order to derive the equations, Kydd et al. classified the tillage operation as primary tillage and secondary tillage. According to Kydd et al., primary tillage is the first tillage operation after the crop is harvested, which might be immediately after harvest or delayed until the following spring. Tillage operations such as weed kill in summer fallow or seedbed preparation were the secondary tillage. The field conditions were classified into heavy and light conditions which was a result of judgement of the

draft characteristics based on soil variables such as type, compaction and moisture content. For example, the first operation in a stubble field which has a high draft characteristic would be called heavy primary tillage. With the classifications above, Kydd et al. utilized regression analysis to derive a number of equations for different types of machines in different field conditions.

Cultivators and disk harrows are the most common tillage implements used on the Prairie. Therefore, the study only deals with the combinations of tractor with cultivators and disk harrows.

a. Cultivators

The draft equations for heavy duty cultivators are:

$$D_t = w(60.7d + 99.6V_d - 1909)/1000 \quad (3.49)$$

in heavy primary tillage and

$$D_t = w(26.9d + 94.3V_d - 458.4)/1000 \quad (3.50)$$

in light primary tillage.

where D_t = draft per metre, kN.

d = tillage depth, mm.

V_d = travel speed, km/h.

w = implement operation width, m.

The draft equations for field cultivators are:

$$D_t = w(26.9d + 94.3\ V_d - 458.4)/1000 \quad (3.51)$$

in heavy secondary tillage and

$$D_t = w(23.6d + 58.0V_d - 655.1)/1000 \quad (3.52)$$

in light secondary tillage. The equation for field cultivators in heavy secondary tillage is the same as heavy

duty cultivators in light primary tillage.

The draft of blade cultivators is predicted from:

$$D_t = w(33.5d + 34.9V_d + 1055.8)/1000 \quad (3.53)$$

in primary tillage and

$$D_t = w(37.3d + 91.6V_d - 702.7)/1000 \quad (3.54)$$

in secondary tillage.

b. Disk harrows

The draft equation for tandem disk harrows is:

$$D_t = w(57.1d + 312\gamma + 15.7V_d - 657)/1000 \quad (3.55)$$

where γ = disk angle, deg.

the equation for a one-way disk harrow is:

$$D_t = w(29.3d + 127.5V_d - 326.8)/1000 \quad (3.56)$$

The slip of the tractor can be calculated from the Wismer and Luth equations once the draft of the implement is determined. For a two wheel drive tractor, the slip is:

$$s = \frac{-1}{0.3C_{n2}} \text{Ln}\left(1-\frac{F_d+W_{d1}(1.2/C_{n1}+0.04)+W_{d2}(1.2/C_{n2}+0.04)}{0.75W_{d2}}\right) \quad (3.57)$$

For a four wheel drive tractor with the dimensions of the front tires and rear tires being the same, the slip is:

$$s = \frac{-1}{0.3C_n} \text{Ln}\left(1 - \frac{F_d+(W_{d1}+W_{d2})(1.2/C_n+0.04)}{0.75(W_{d1}+W_{d2})}\right) \quad (3.58)$$

where C_n = wheel numeric.

For a front wheel assist tractor, the slip is obtained by solving the equations of front thrust, rear thrust and drawbar pull.

The rest of the tractor-implement performance such as travel speed, drawbar power or power requirement of the implement, tractive efficiency, and fuel consumption are

determined by equations described in the tractive model and the fuel consumption model after the slip is obtained.

3.4 Features and Algorithms of the Computer Model

The computer program listed in Appendix A2 consists of a main section and a number of subroutines programmed with BASICA language. The program execution can be performed on a microcomputer (IBM PC, for example). The inputs of the model may be either entered from the keyboard or read from an input file. Changes can be made in the input parameters and new outputs generated if several sets of input data are required.

Two alternatives available for users are the prediction of tractor performance and the prediction of the combination of tractor and implement. An iterative method is required for solving the group equations of the tractive performance since both the dynamic axle loads and the drawbar pull are unknown. Slip is taken as the independent variable for the prediction of tractor performance. The initial value of slip is set to zero. Then, the computer performs the calculation by increasing the slip value by a specified increment. The drawbar pull and dynamic axle loads are calculated by using the iterative method. The process is repeated until the slip reaches the optimum value at which the drawbar power is maximum or the engine is overloaded.

For the tractor-implement performance, the tillage depth is the independent variable. The draft is calculated

first. The iterative method is used in the model since the draft of the implement relates to tillage depth and travel speed which in turn is affected by the draft.

The model is capable of simulating tractor or tractor-implement performance in the field. The overall algorithm of the computer model is described by the flowchart as shown in Appendix A1.

The procedure for the prediction of tractor performance can be detailed as follows.

1. Input (from keyboard or an input file) the physical parameters of the tractor, engine characteristics, soil strength properties, and simulation control parameters.
2. Initialize the variables of the model. Interpolate the engine torque-speed curve and calculate the gear ratio. Estimate the dynamic axle loads, drawbar pull, etc. as old values.
3. Calculate the motion resistance, thrusts, dynamic axle loads, and drawbar pull.
4. If the drawbar pull is less than zero, increase the slip by a small increment and restart the calculation from step 3.
5. Determine the maximum difference between the old and the new values among dynamic axle loads, motion resistance, thrusts, motion resistance arms, wheel numerics, and drawbar pull.
6. If the maximum difference in step 5 is not within specified accuracy (0.001 for example), the newly

computed values become estimated values (or old values) and the calculation is restarted from step 3. Otherwise the calculation goes to the next step.

7. Calculate the engine speed, engine torque, travel speed, drawbar power, and tractive efficiency.
8. Compare the drawbar power with drawbar power at the previous slip value. If the drawbar power is less than the previous one, the optimum slip is the previous slip and the calculation goes to step 12.
9. Compare the engine torque with the maximum engine torque. If the engine torque is greater than or equal to the maximum torque, calculation will go to step 12.
10. Calculate the fuel consumption.
11. Increase the slip by a small increment and restart the calculation from step 3.
12. The results are printed at the slip interval until the maximum drawbar power or maximum engine torque is reached.

The calculation procedure for tractor-implement combination performance is similar to that for tractor performance. The procedure is listed as follows.

1. Input the tractor and engine parameters, soil measurements, implement parameters and simulation control parameters.
2. Initialize the variables. Interpolate the engine torque-speed curve and calculate the gear ratio. Estimate the travel speed and the draft as old values.

3. Calculate the draft, slip, thrusts, axle torque, engine torque, engine speed, and travel speed.
4. Compare the old and the new draft and travel speed values. If not within specified accuracy, the newly computed speed and draft become the estimated speed and draft. The calculation is restarted from step 3.
5. Calculate the slip, tractive efficiency, drawbar power or power requirement of the implement.
6. Calculate the fuel consumption.
7. Test the depth. If the depth is less then 125 mm, increase the depth by 25 mm and restart the calculation from step 3.
8. Print out the results at a depth interval of 25 mm.

3.5 Input and Output of the Computer Model

The information required by the computer model is the tractor's physical and geometric characteristics, soil strength properties and implement parameters. a sample of the input file is shown in Appendix A3.

The tractor input parameters are listed below along with their corresponding model variable names.

1. Engine speed (unloaded, rpm), ENSP1.
2. Engine maximum speed (rpm), MENSP.
3. Rated engine speed (rpm), RENSP.
4. Engine speed at 85% load (rpm), ENSP85.
5. Engine speed at 21% load (rpm), ENSP21.
6. Engine displacement (cm^3), DISPM.
7. Engine Power(PTO)-speed(crankshaft) relationship (six pairs of points,rpm,kW), S(1),P(1)...,S(6),P(6).
8. Rated PTO power (kW), RPTOP.
9. PTO power at 85% load (kW), PTOHP85.
10. PTO power at 21% load (kW), PTOHP21.

11. No load travel speed (km/h), TVSP.
12. Front axle static weight (kg), FSAW.
13. Rear axle static weight (kg), RSAW.
14. Front ballast (kg), FBALAS.
15. Rear ballast (kg), RBALAS.
16. Wheel base (m), WHBS.
17. Drawbar height (m), DRHT.
18. Front unloaded tire diameter (m) and width (m), FTDIA,FTWID.
19. Rear unloaded tire diameter (m) and width (m), RTDIA,RTWID.
20. Front tire inflation pressure (kPa), FINPR.
21. Rear tire inflation pressure (kPa), RINPR.
22. Net heat value of the fuel (mJ/kg), NHV.
23. Fuel consumption at 85% load (kg/h) and 21% load (kg/h), FUEL85,FUEL21.
24. Drive type (DWT,FWT,FWA), DOPT$

The engine characteristics of the Case International model 2394 tractor are shown in Appendix D.

The inputs of soil strength properties are as follows.

1. Front cone index (kPa), CONI.
2. Rear cone index (kPa), RCONI.
3. Internal friction angle (rad), ALFA.
4. Cohesion (kPa), COHN.
5. Soil deformation modulus (m), CONSTK.

If the prediction based on soil cone index is preferred, only the first two parameters are required. For a two wheel drive tractor, the front and rear cone indices are the same. For a four wheel drive tractor, they may not be the same since the soil strength may increase after the first pass.

Additional information about the implement is required for the tractor-implement combination option.

1. Implement operation width (m), IWID.
2. Tillage depth (mm), IDEP.
3. Implement type, ITYP$

To complete the input information the following information is needed.

1. Gear number, GNUM$.
2. Soil texture, SLTP$.
3. Tractor model, TNAME$.
4. Field number, FLDNUM$.
5. Operation date, OPDT$.

The outputs of the model are tractive efficiency, drawbar pull, drawbar power, slip, travel speed, engine speed, tillage depth, and fuel consumption at each interval of slip or depth.

Samples of predicted performance are shown in graphic form for the Case International 2394 tractor. Figures 3.5, 3.6 and 3.7 show detailed tractor performance at maximum throttle setting for one soil condition (CI=900 kPa) with ballast of 2177 kg for gears #7, #9, #10, #11, and #13.

The performance with various soil conditions and rear ballasts in #9 gear are shown in Figures 3.8 to 3.11. Two cone index values were used. For each soil condition, two levels of ballast (0 and 2177 kg) were added.

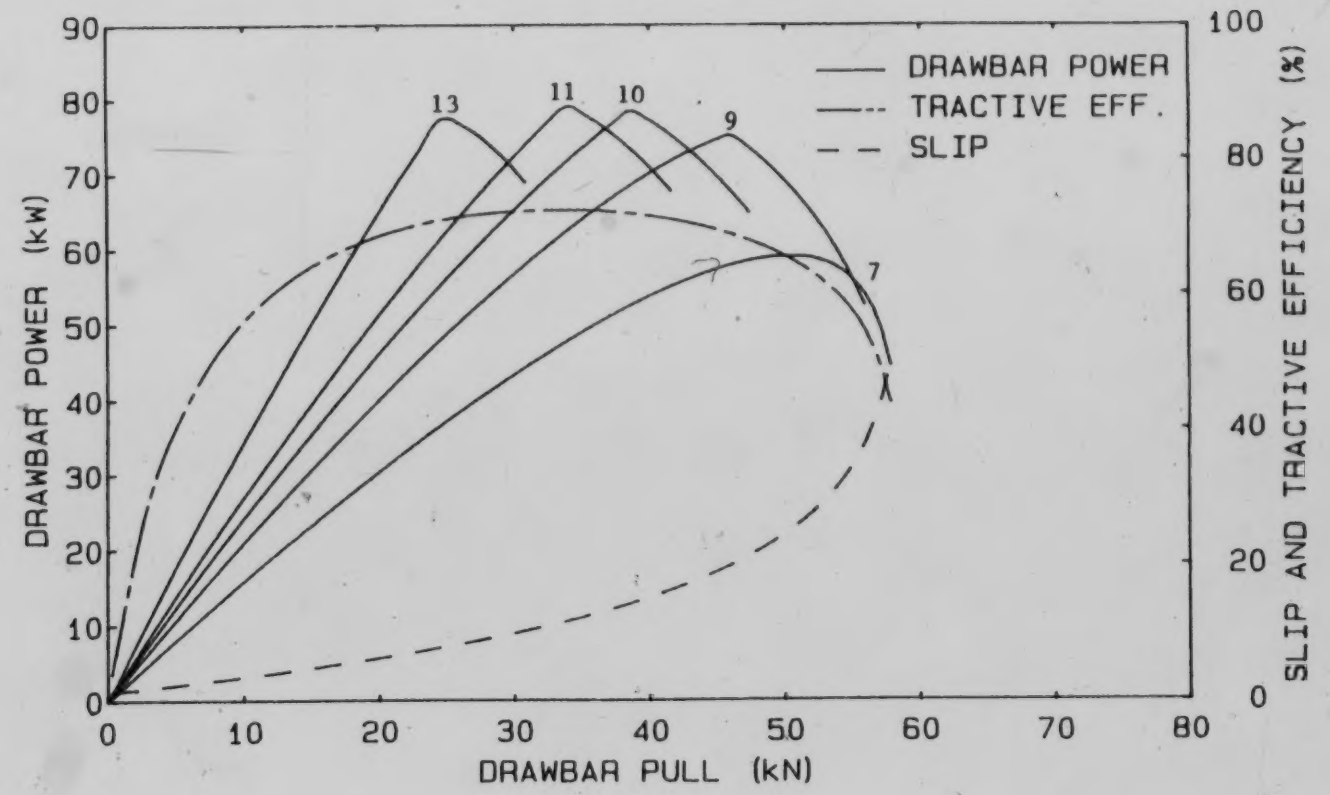


Figure 3.5 Predicted drawbar power, slip, and tractive efficiency versus predicted drawbar pull in gears #7,#9,#10,#11,#13

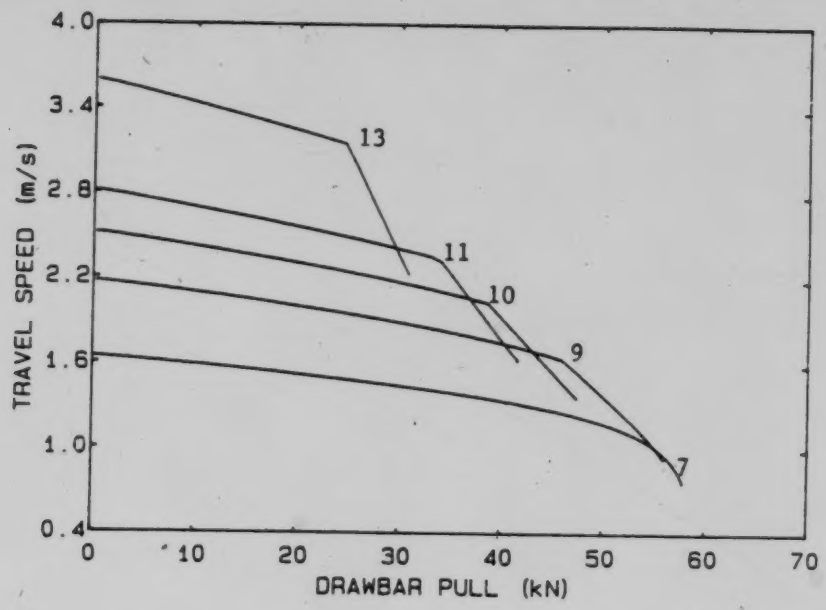


Figure 3.6 Predicted travel speed versus predicted drawbar pull in gears #7,#9,#10,#11,#13

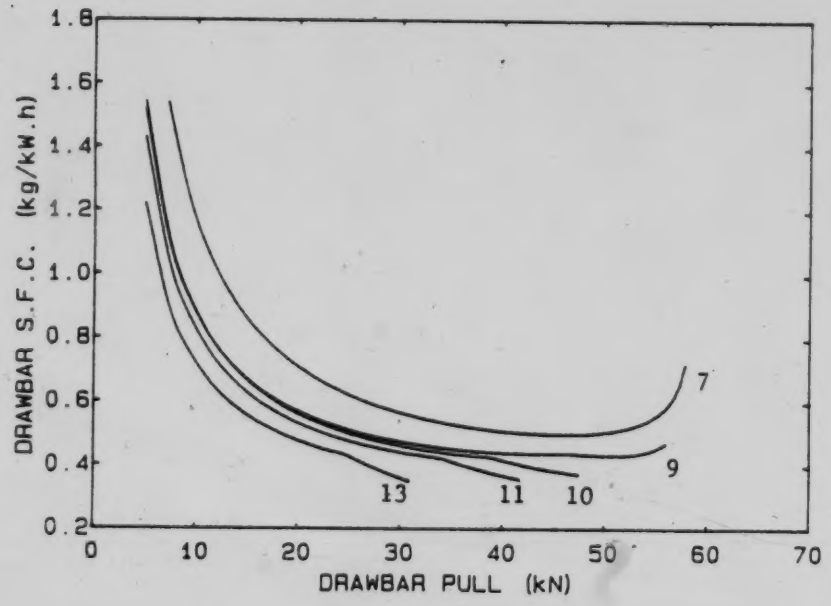


Figure 3.7 Predicted fuel consumption versus predicted drawbar pull in gears #7,#9,#10,#11,#13

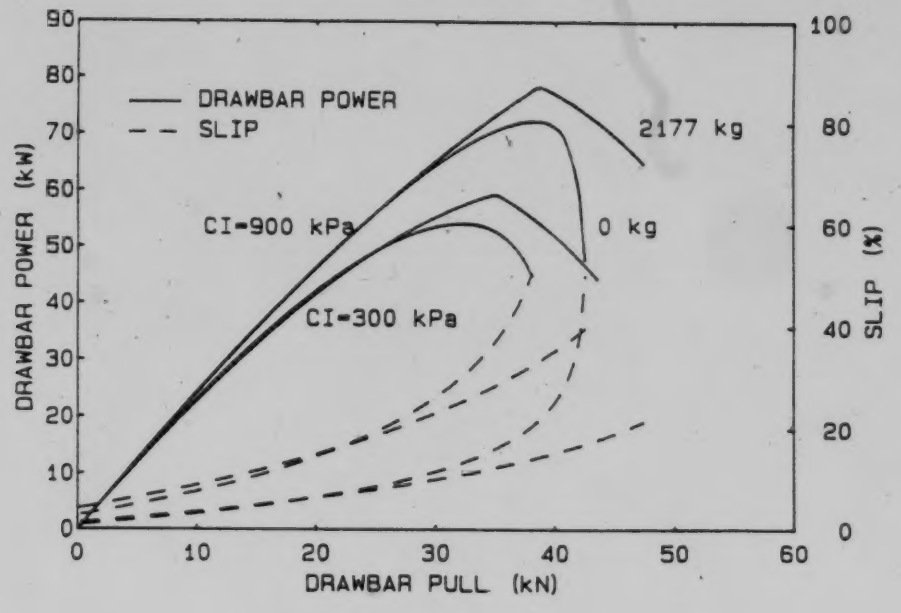


Figure 3.8 Predicted drawbar power & slip versus predicted drawbar pull with ballast of 0 & 2177 kg and two CI values

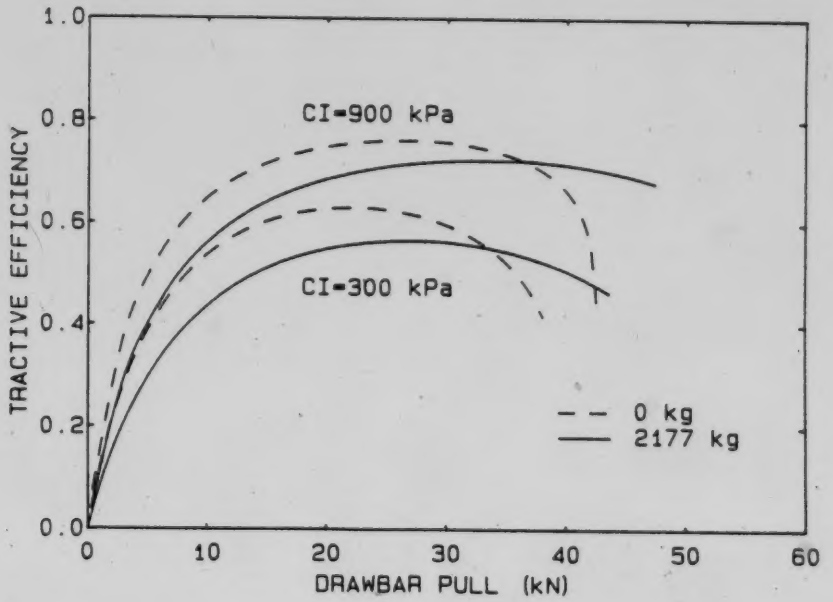


Figure 3.9 Predicted tractive efficiency versus predicted drawbar pull with ballast of 0 & 2177 kg and two CI values

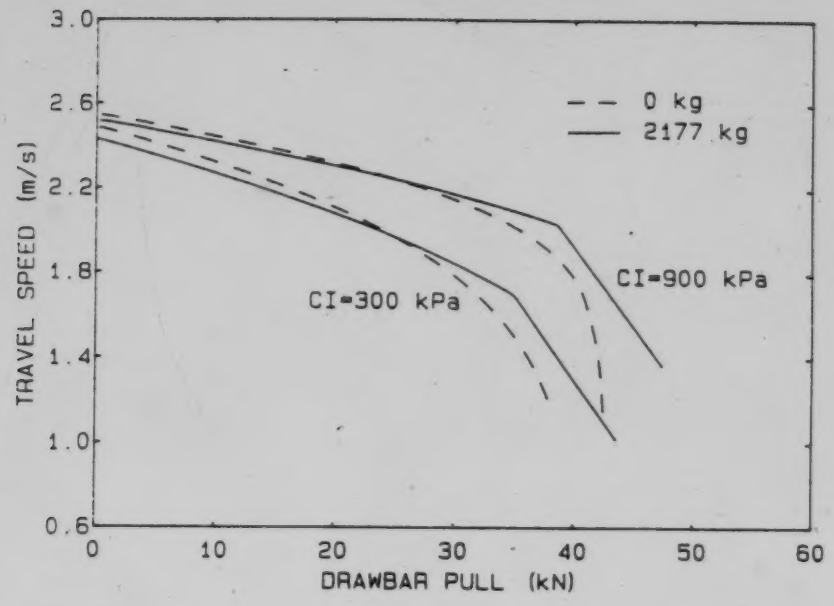


Figure 3.10 Predicted travel speed versus predicted drawbar pull with ballast of 0 & 2177 kg and two CI values

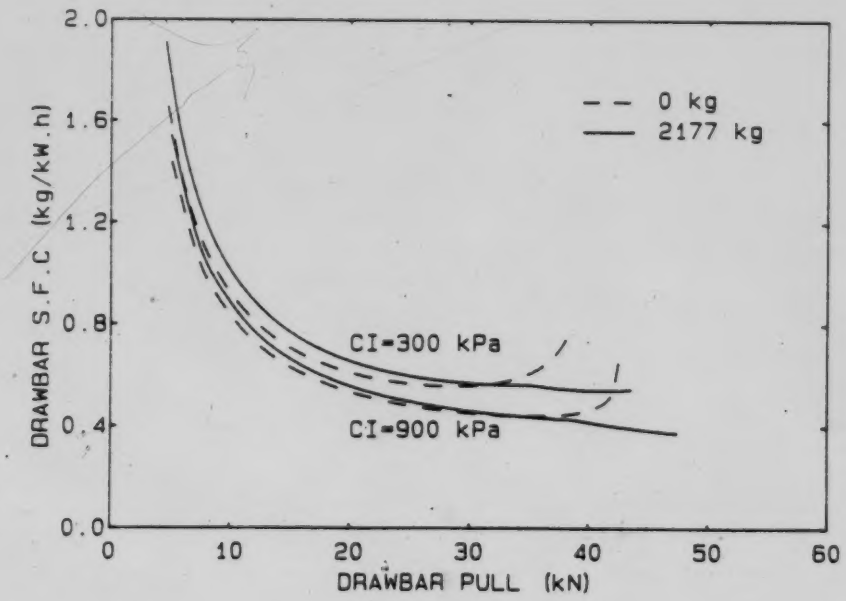


Figure 3.11 Predicted fuel consumption versus predicted drawbar pull with ballast of 0 & 2177 kg and two CI values

4. COLLECTION OF FIELD TEST DATA

The field test data for comparison with the model predicted tractor performance were collected as part of the Fuel Usage Demonstration project conducted by Alberta Agriculture and Olds College. The tractor used in the project was a Case International model 2394 farm tractor as shown in Figure 4.1. The tractor equipped with dual 20.8(R)38 rear tires and 16.5L-16.1 front tires had a 6-cylinder turbo-charged diesel engine, maximum PTO power of 120 kW at 2100 rpm rated engine speed.

The tractor was loaded by a cultivator in the field. The cultivator was a 7.6 m wide heavy duty Case International chisel plow equipped with 0.41 m wide sweeps spaced at 0.305 m.

As a part of a three year project, the tractor and cultivator were used in the spring and summer of 1987 over a wide range of soils and field conditions in Alberta. The purposes of the project were (a) to demonstrate to farmers the improvements in fuel efficiency that could be achieved by gearing up-throttling down at less than full load, (b) to demonstrate proper tractor ballasting, and (c) to develop a data base of power and fuel consumption for tillage operations under Alberta soil and field conditions. Most of the data collected during the spring and the early summer of 1987 in the project were used in this study.

Figure 4.1 The tractor and the cultivator used in the project conducted by Alberta Agriculture and Olds College.

4.1 Instrumentation of the Tractor and Cultivator

The tractor and cultivator were instrumented with an electronic monitoring and computer data acquisition system to measure and display engine speed, ground speed, axle speed, fuel consumption, tillage depth, and drawbar pull etc. Drawbar performance and fuel consumption were the variables of greatest interest in this study. Chang and Green (1987) have described the instrumentation in considerable detail. The instrumentation is briefly summarized as follows:

1. Drawbar pull meter

The drawbar pull was measured by a drawbar pull meter. The drawbar pull meter had two steel beams with pinned ends connected to a frame which was bolted to the hitch of the tractor. The implement end of the hitch was connected to the centers of the two beams. Strain gauges were mounted on the two beams as shown in Figure 4.2. The strain gauges were configured in a Wheatstone bridge and designed to cancel vertical and lateral loads. The maximum load which the pull meter could handle was 112 kN.

The tractor load was supplied by towing a cultivator. The load could be changed by adjusting the tillage depth of the cultivator.

2. Engine speed sensor

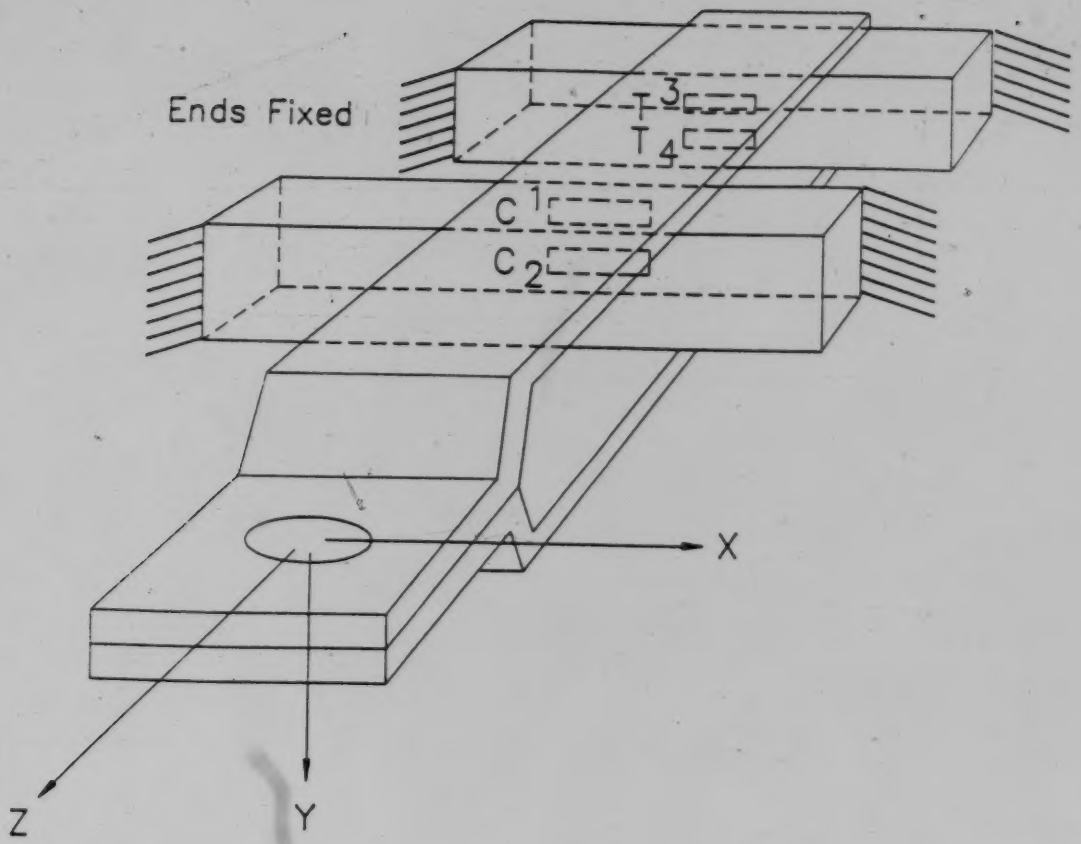
This sensor was located on the drive gear of the fuel injection pump. As a gear tooth passed by the magnetic sensor, a pulse was generated. The frequency of the pulse was proportional to the speed of rotation of the drive gear.

3. Drive axle speed sensor

The sensor was also a magnetic pick-up sensor located near the crown gear on the rear differential. The output signal of the sensor was conditioned by the electronic monitoring system before being sent to the computer.

4. Ground speed sensor

The actual travel speed in the field was measured by a Doppler radar sensor. The unit was aimed towards the rear of the tractor at an angle of 35 degrees to the horizontal



T^3, T_4 = Strain gauges, tension.
C^1, C_2 = Strain gauges, compression

Figure 4.2 Drawbar pull meter used to measure drawbar pull (Adapted from Chang and Green, 1987)

direction. The theoretical travel speed for each gear was measured on a hard smooth surface with zero drawbar pull.

5. Depth of tillage

The depth of tillage was measured by a gauge wheel which was mounted on a lever arm. An angular potentiometer was connected to the pivot of the lever arm to measure the angular displacement of the lever arm. The depth which ranged from zero to 150 mm was determined from the angular displacement of the lever arm.

6. Fuel flow measurement

A Micro Oval II fuel flow sensor from Oval Engineering Co. Ltd. was installed in the supply line to a float tank as shown in Figure 4.3. A supply line from the float tank supplies fuel to the injector pump and the injector return fuel flows back to the float tank. A flow valve mechanism in the float tank maintained the fuel level constant. Therefore, the fuel flow meter measured the net fuel flow to the engine.

7. Data acquisition system

The data acquisition system consisted of a microcomputer which could acquire and store the data collected from up to 33 input channels. The rate at which data was scanned could be set for each individual channel from a maximum scanning rate of once per second to a minimum scanning rate of once every 32767 seconds. The outputs from all the measurement sensors were fed into the computer. The computer sampled and recorded the instantaneous reading from

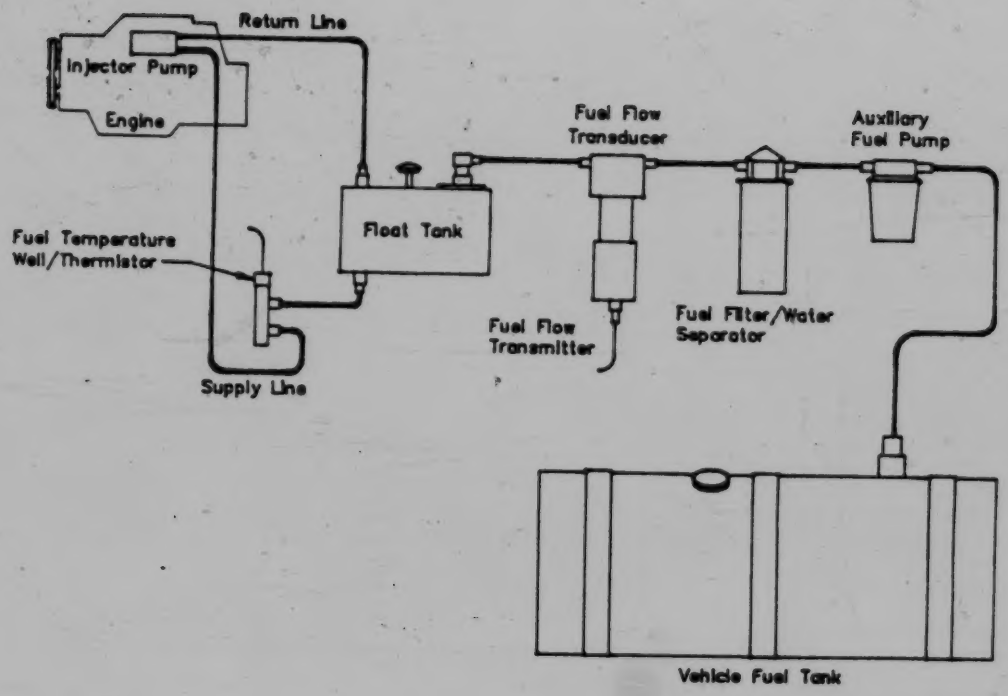


Figure 4.3 Fuel measurement system used to measure fuel consumption

(Adapted from Chang and Green, 1987)

input channels every second onto a magnetic bubble memory cartridge which was capable of storing 210 K bytes of data. Generally, thirty sets of sensor readings were accumulated over a 30 second run and the averages were stored in the memory system.

The data stored in the memory system could be down-loaded onto floppy diskettes by temporarily hooking-up a Compaq Personal Computer to the data acquisition system at the end of the field test.

The data acquisition system interfaced with the operator through a remote keyboard/display unit. After each test run, the test data could be displayed on the display unit or printed on a printer.

4.2 Equipment for Soil Strength Measurements

The equipment for soil mechanical property measurements in this study consisted of two penetrometers and a shear meter.

a. Penetrometers

The penetrometers used in the study were an electric tripod penetrometer and a hand operated penetrometer. The hand operated penetrometer was used only as an alternative to the tripod penetrometer for fields where the soils were too firm or not suitable for using the tripod penetrometer. The hand operated penetrometer had a spring which compressed proportional to the load applied to the cone and a chart recorder plate which recorded the penetration load and the

Figure 4.4 The load cell and the potentiometer for measuring penetration force and depth of the penetrometer.

depth. Two cone base sizes were used. The cone with 130 mm^2 base area was used for firm soils. For other soils, the 323 mm^2 base cone was used. The cone angle for each cone was 30 degrees.

The electric penetrometer as shown in Figure 4.4 consisted of a thirty degree cone of 323 mm^2 base area which was fixed at the end of a 15.9 mm diameter shaft. The shaft

was connected to an electric drive worm gear cylinder which could move up and down. A load cell from Strainsert Company capable of measuring up to 13 kN load was mounted between the shaft and the cylinder to measure the penetration force. The depth of the penetration was detected by a linear potentiometer from Durham Instruments Inc. fixed between the shaft and the frame. The effective measuring length of the potentiometer was 210 mm. The maximum measuring depth of the penetrometer was 152 mm and the penetration rate was 30 mm per second.

The signals from the load cell and the potentiometer were amplified first and then recorded by a HP 7034A X-Y recorder.

b. Shear meter

The shear meter used in this study as shown in Figures 4.5 and 4.6 was a hydraulic operated apparatus built in the shop in the Agricultural Engineering Department. The meter had a shear ring of 152.4 mm inside diameter and 203.2 mm outside diameter which was connected to a hydraulic rotary actuator. Eighteen grousers of 6 mm height and 2 mm thick were mounted on the shear ring. The normal pressure of the shear ring was provided by putting weights on the top of the shaft connected to the ring. The four levels of normal pressure used were 19.9 kPa, 39.3 kPa, 70.7 kPa, and 86.5 kPa. For each level, the shear ring was rotated 360 degrees at a constant speed of one rpm. The speed could be changed by adjusting the flow valve. The torque applied to the shear

Figure 4.5 The shear ring of the shear meter used for soil strength test.

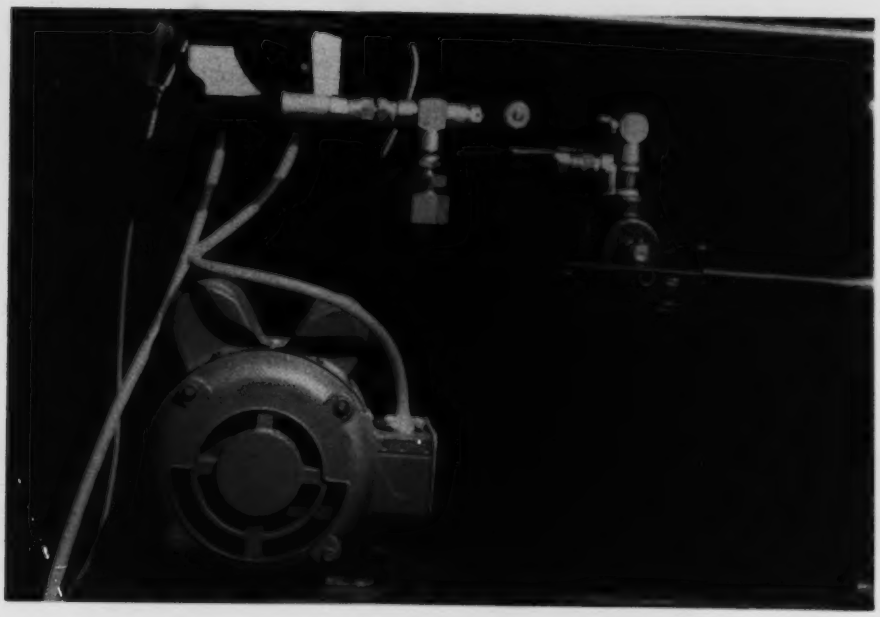


Figure 4.6 The pressure transducer for measuring the hydraulic pressure of the shear meter.

ring was measured indirectly by a hydraulic pressure transducer which could measure up to 20.7 MPa. The pressure transducer was located between the flow valve and the hydraulic rotary actuator. The output from the transducer was sent to an amplifier and recorded by the HP 7034A X-Y recorder with the time base on the X axis which indicated the displacement of the shear ring. The hydraulic pressure was converted into torque according to the calibration curve of the hydraulic rotary actuator provided by the manufacturer.

4.3 Field Test Procedures

The tractor and the cultivator had been used for developing a data base in about fifty fields in Alberta in the spring of 1987. The test procedure was similar for each field. The field was located first. The next step was to complete a data sheet for describing soil type and field conditions. These include soil zone, texture, moisture content, bulk density, firmness, and field conditions. Then, a plot of about two hectares with a minimum length of 150 metres in the field was located. The plots were relatively level with uniform surface conditions. The data base runs were conducted at tillage depths of 25, 50, 75, 100, and 125 mm and a field speed of about 8 to 9 km/h. Three runs were performed for each depth. The tractor was operated at full throttle and rear wheel ballasting of 2177 kg during the test runs.

At the same time, the penetrometer tests before and after tire traffic and the shear tests were conducted. At least five tests before tire traffic and five tests after tire traffic for the penetrometer tests in or near the plot were done for each field. For the shear test, generally, one or two sites which could best represent the soil in the plot were located. Four levels of normal pressure were applied. Typical cone index-depth curves for a penetrometer test and shear stress-displacement curves for shear test are shown in Appendix B. The soil cone indices for each field were averaged over the top 152 mm depth by using the digitizing equipment and software located in the Agricultural Engineering Department.

The data that were collected by the on-board computer for each run are listed as follows:

1. date and time
2. total tractor weight
3. gear number
4. engine speed
5. drawbar pull
6. fuel consumption
7. ground speed
8. wheel speed
9. exhaust temperature
10. tillage depth
11. field location

The variables such as slip, drawbar power, fuel efficiency, and tractive efficiency were calculated by the on-board computer and stored in the memory.

The data collected during the demonstration in the early summer of 1987 were from ten fields. The demonstration included ballast runs, gear up-throttle down runs, travel speed runs, and depth runs. The field area used for each demonstration was about ten hectares. The information collected for soils, the soil tests and the depth runs were the same as those described previously. The procedures of ballast runs, gear up-throttle down runs, and travel speed runs are briefly described as follows.

Ballast runs: Three runs were made at each ballasting weight of 0, 1088.5, or 2177 kg at field speeds of 6.4, 8.4, and 12 km/h. The tractor was operated at full throttle setting and the cultivator was lowered to load the engine speed down to its rated speed of 2100 rpm. Total tractor weight was changed by adding or removing steel weights on the drive wheel axle.

Gear up-throttle down runs: These run were done with rear wheel ballast of 2177 kg. The initial run was in gear #10 at full throttle and full load. Then, the load was reduced to 50% of the full load and the second run was done similarly to the first run. The third run was done at reduced throttle to obtain desired percentage of rated engine speed. The above three runs were repeated in gears #11, #12, and #13.

Travel speed runs: The runs were done at the same tillage

depth but at different travel speeds. Normally four runs were performed.

The data from the fields which were on rolling hills and were shallow cultivated or had a lot of residue on the surface were not used in the study.

5. VALIDATION OF THE MODEL FOR A TWO WHEEL DRIVE TRACTOR WITH DUAL TIRES

The model was validated by comparing the predicted performance with the measured performance. The field test data were from the Fuel Usage Demonstration project conducted by Alberta Agriculture and Olds College. The model validation was divided into three parts. Firstly, the tractive part of the model was validated in terms of drawbar pull and drawbar power. The second part was the validation of the fuel consumption and the third part was the comparison of predicted versus measured tractor-implement performance. The tractive portion of the model was the foundation for the remaining two parts of the model.

Only the predicted performance of a two wheel drive tractor with dual tires was validated in this study since the field test data were collected from a two wheel drive tractor with dual tires.

5.1 Predicted Versus Measured Tractive Performance

The predicted tractive performance in both approaches was compared with the measured performance in terms of drawbar pull and drawbar power. The comparison was made in different gears with ballast of 2177 kg and full throttle setting.

For approach I, the selection of the cone indices input to the model affected the accuracy of the prediction. The cone indices used in this study were 0-150 mm average cone

indices. Figure 5.1 shows the comparison of predicted versus measured drawbar pull for approach I by using the cone index before traffic for all fields. The scatter shown in Figure 5.1 might be due to some highly compactible soils. The cone indices before traffic of highly compactible soils could not closely describe the soil strength properties under the wheel since the soil tends to compact and increase in strength under heavy loads. Figure 5.2 shows the comparison of drawbar pull with cone indices before traffic for firm soil (cone index before traffic greater than 900 kPa) and cone indices after traffic for other soils. Comparing Figure 5.1 with Figure 5.2, the accuracy of the prediction is improved considerably by correctly selecting the cone index for each field. Figure 5.3 shows the comparison between predicted and measured drawbar power for approach I.

For approach II, Figure 5.4 and Table 5.1 show the comparison of predicted with measured drawbar pull with the input of soil deformation modulus at 86.5 kPa which was the maximum normal pressure applied to the shear meter. The accuracy of the prediction could be improved by using the soil deformation modulus at or near 110 kPa which was approximately the contact pressure between the wheel and soil. The soil deformation modulus at or near the contact pressure was estimated based on the measured relationship between deformation modulus and pressure. Figure 5.5 shows the comparison of drawbar pull with soil deformation modulus at 110 kPa. Comparing Figure 5.4 with Figure 5.5, the

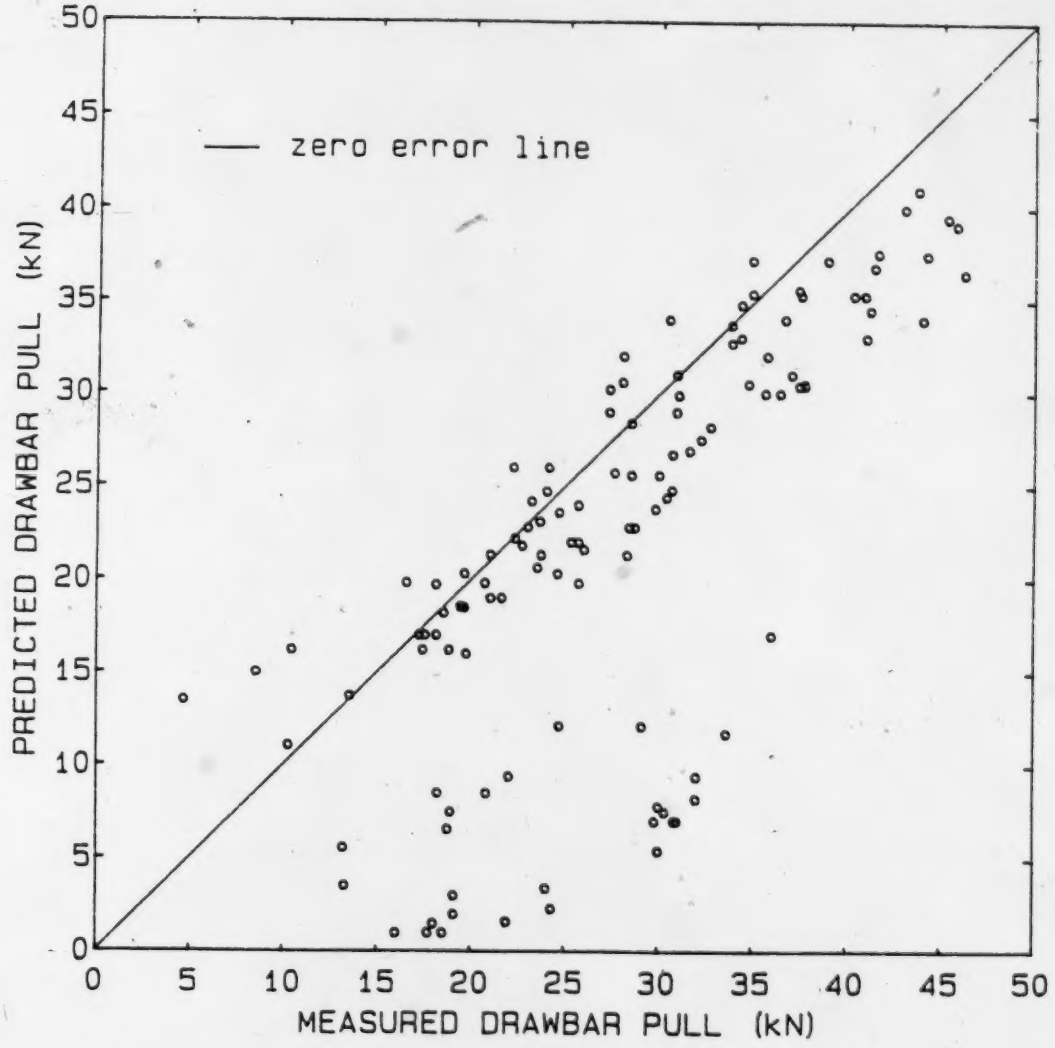


Figure 5.1 Comparion of predicted and measured drawbar pull with cone index before traffic for approach I

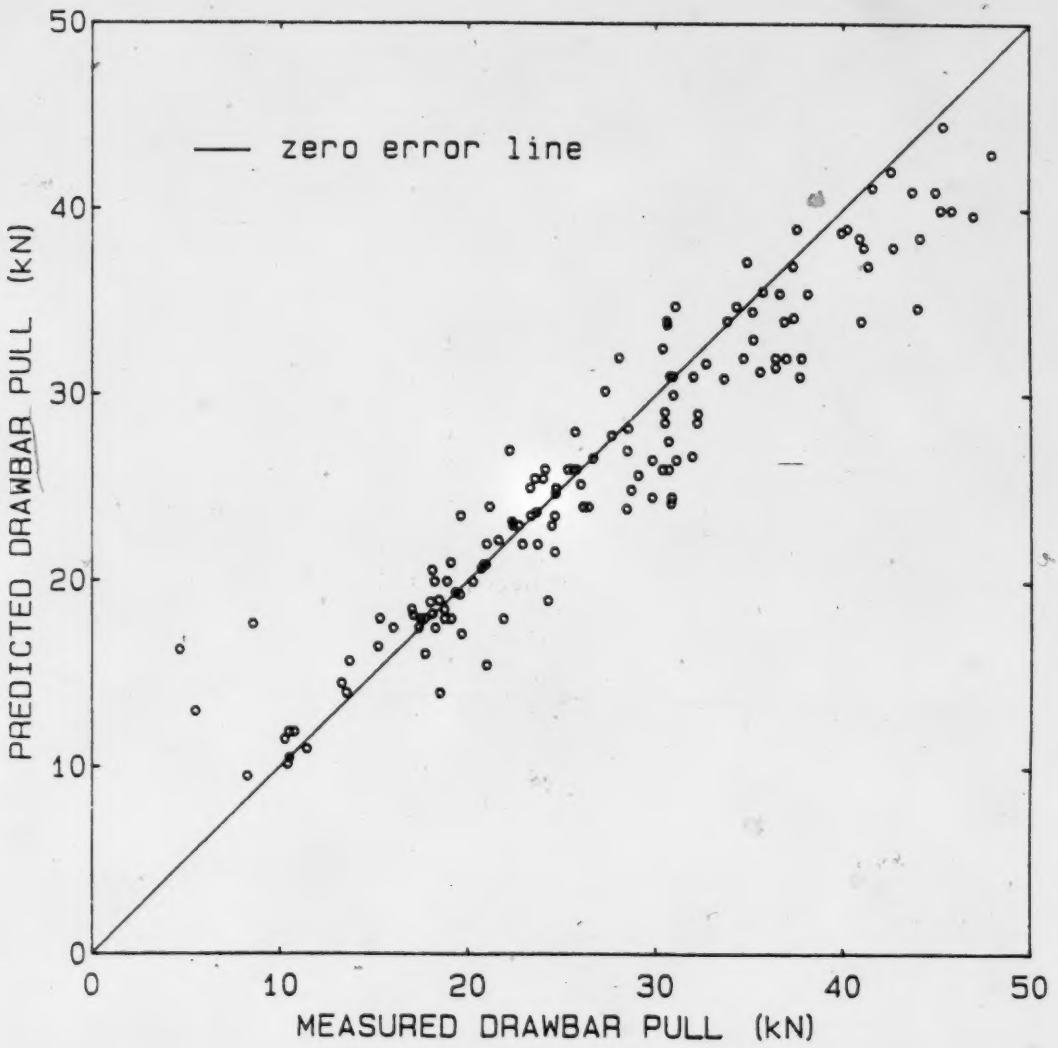


Figure 5.2 Comparison of predicted and measured drawbar pull with selected cone index for approach I

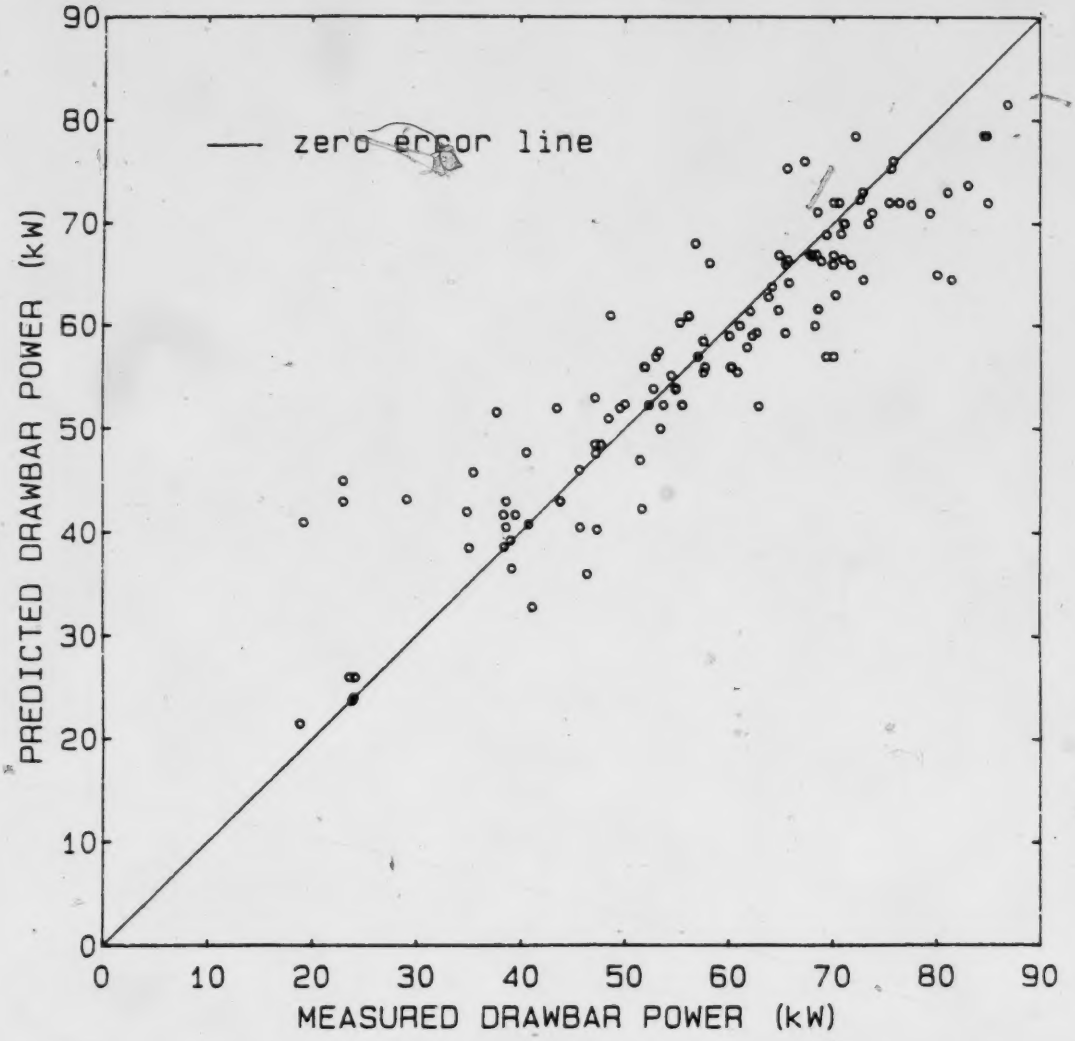


Figure 5.3 Comparison of predicted and measured drawbar power for approach I

accuracy of the prediction using the soil deformation modulus at or near the contact pressure is improved by 10% for approach II. Figure 5.6 shows the comparison between predicted and measured drawbar power for approach II.

Table 5.1 Statistical comparison of predicted and measured drawbar pull for approach II with soil deformation modulus at 86.5 kPa.

Relative error (%)	mean difference (kN)	Standard deviation of mean difference (kN)	95% confidence interval estimate of true mean difference (kN)
20	1.6	0.42	$0.76 \leq \mu_d \leq 2.44$

For both approaches, the statistical comparisons are shown in Table 5.2 for drawbar pull and Table 5.3 for drawbar power. The relative error is an accuracy measurement of the prediction. The mean difference indicates the tendency for the model to predict higher or lower than the measured values. The standard deviation of mean difference determines the variation of the mean difference.

Compared with the prediction by approach I, the accuracy of the prediction by approach II improved about 1%. The difference between the predictions by approach I and approach II, however, is not significant statistically. Figure 5.2 and Figure 5.5 show that when the drawbar pull was large, both approaches appeared under-predicted which is probably due to an increase in soil strength under the wheel when the wheel is subjected to high dynamic load.

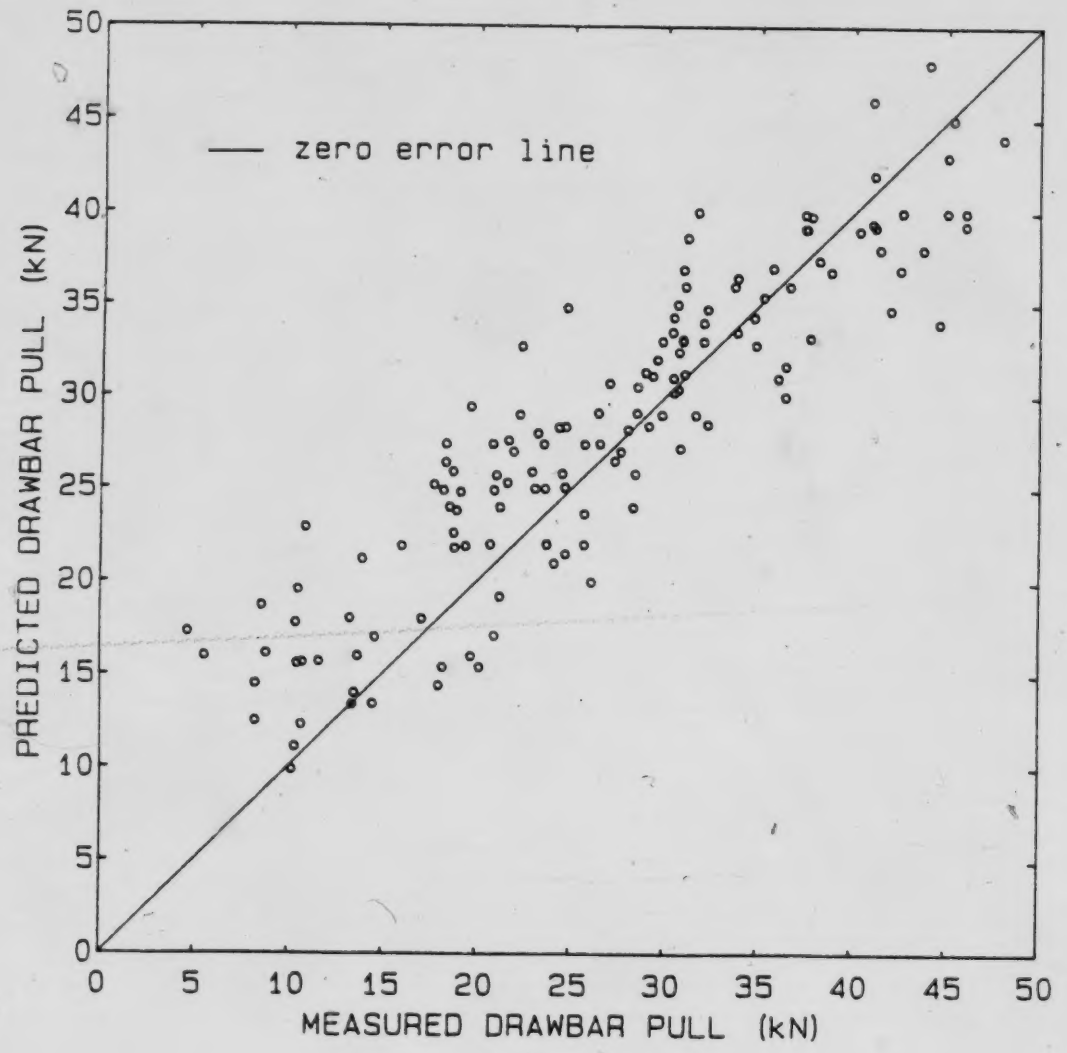


Figure 5.4 Comparison of predicted and measured drawbar pull with soil deformation modulus at 86.5 kPa for approach II

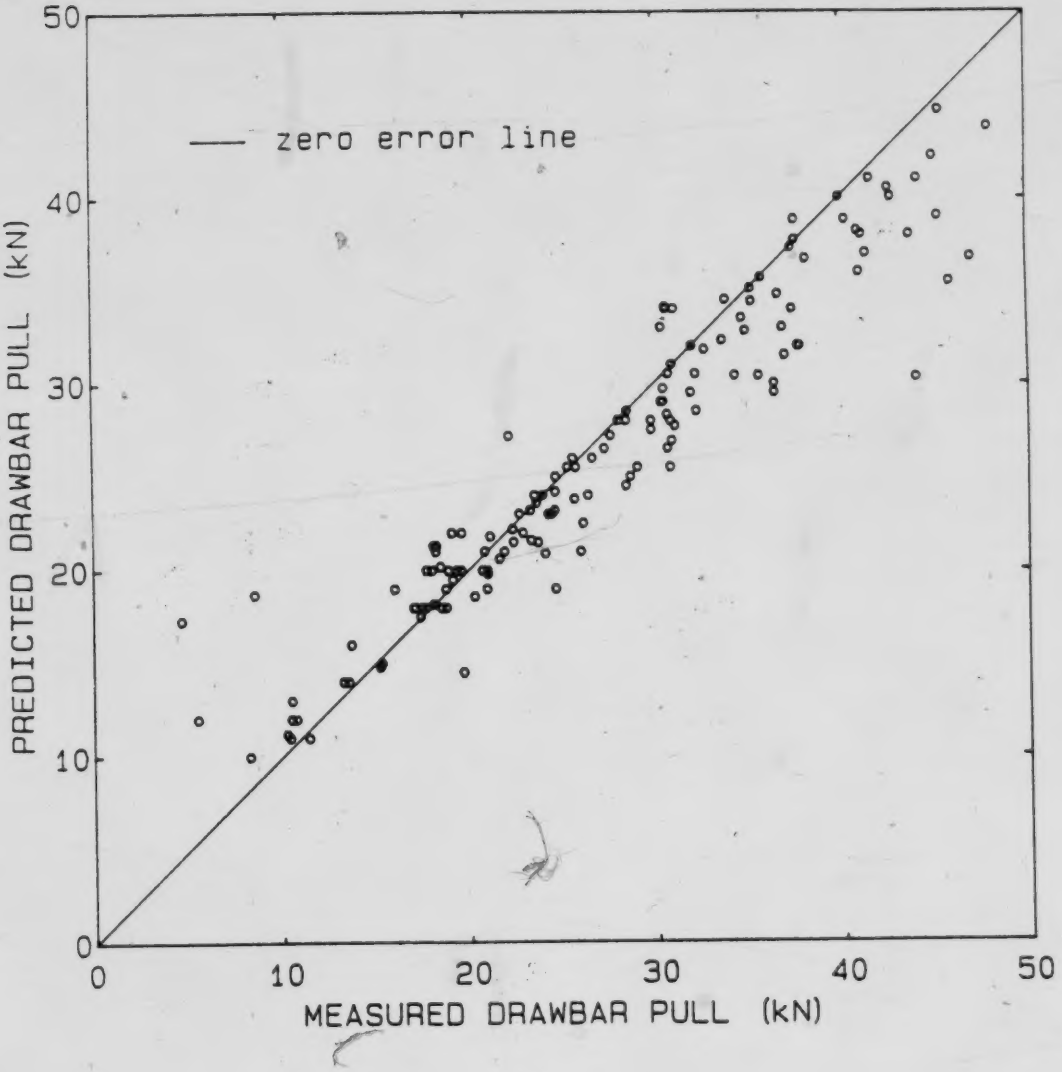


Figure 5.5 Comparison of predicted and measured drawbar pull with soil deformation modulus at or near 110 kPa for approach II

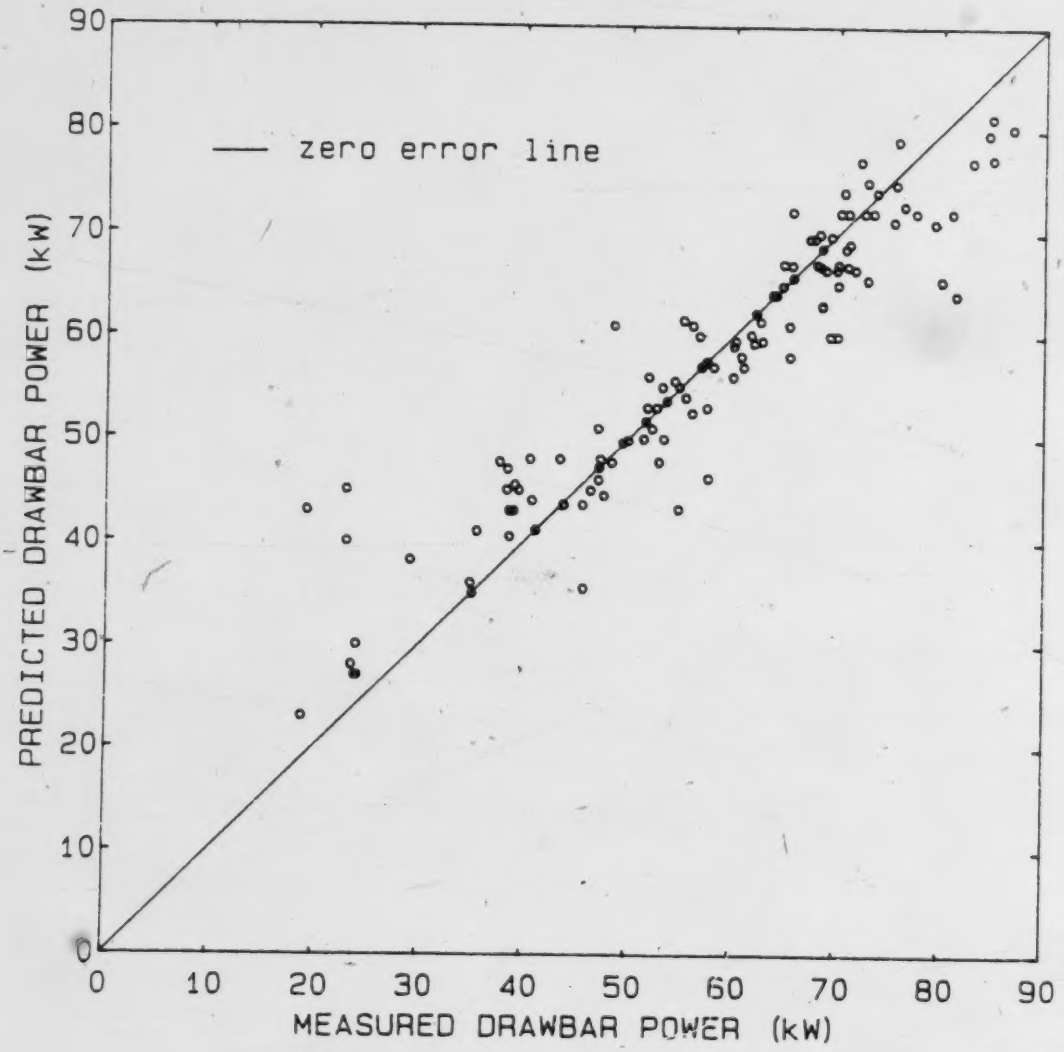


Figure 5.6 Comparison of predicted and measured drawbar power with soil deformation modulus at or near 110 kPa for approach II

Table 5.2 Statistical comparison of predicted and measured drawbar pull

Approach	Relative error (%)	mean difference (kN)	Standard deviation of mean difference (kN)	95% confidence interval estimate of true mean difference (kN)
I	11	-0.97	0.24	$-1.45 \leq \mu_d \leq -0.49$
II	10	-1.02	0.22	$-1.46 \leq \mu_d \leq -0.58$

Table 5.3 Statistical comparison of predicted and measured drawbar power

Approach	Relative error (%)	mean difference (kN)	Standard deviation of mean difference (kN)	95% confidence interval estimate of true mean difference (kN)
I	9	-0.6	0.57	$-1.74 \leq \mu_d \leq 0.54$
II	8	-0.43	0.5	$-1.43 \leq \mu_d \leq 0.57$

Figure 5.7 shows the comparison of predicted and measured drawbar pull versus slip for a typical field. The predicted pull-slip curves are in good agreement with the measured curve. The shear parameters measured for several fields were under-valued. The comparison of predicted with measured drawbar pull for one such field is shown in Figure 5.8. The under-valued soil measurements might be caused by experimental errors or by the residue and roughness of the field surface.

The scatter of the points in the figures may be due to soil variation and experimental errors. Overall, the predicted tractive performance of a tractor operating in summer fallow and stubble fields which are relatively level

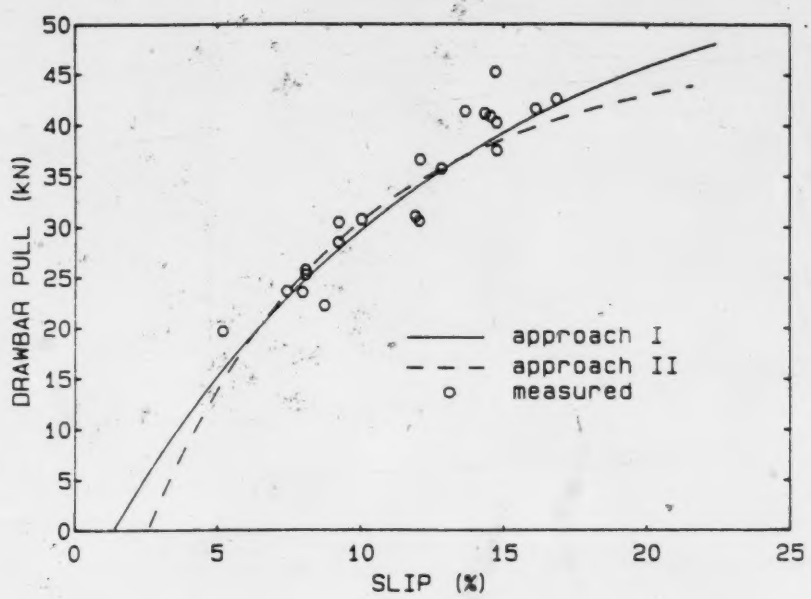


Figure 5.7 Comparison of predicted with measured drawbar pull for a typical field

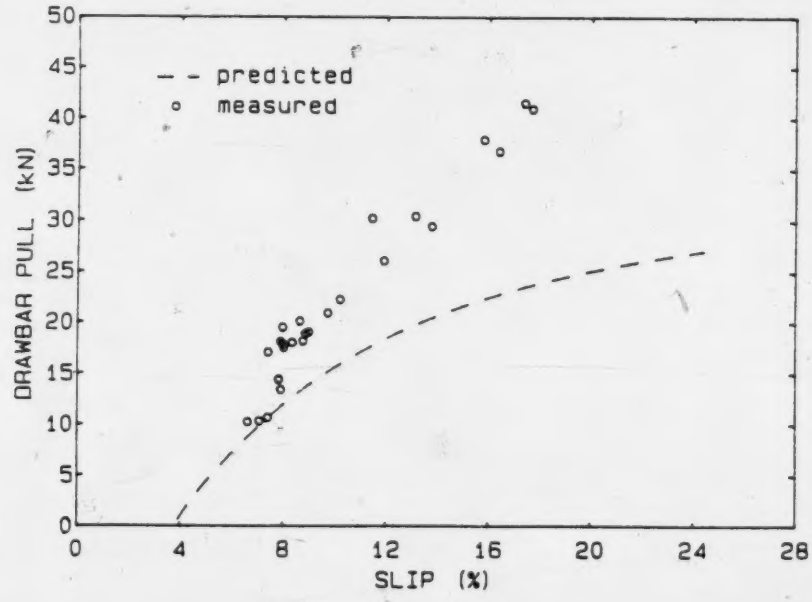


Figure 5.8 Comparison of predicted with measured drawbar pull for approach II for a field in which the soil shear parameters were under-valued

and have not much residue and green growth is reasonably accurate.

5.2 Predicted Versus Measured Fuel Consumption

The prediction of tractor fuel consumption in the field requires the prediction of drawbar power which includes the influences of tractive performance. Comparisons were made between the predicted and measured tractor fuel consumption under varing drawbar loads. Ten typical fields were selected to make the comparison and to determine the accuracy of the prediction. The comparison was made in several gears with one ballast level of 2177 kg and full throttle setting. The soil property input was only cone index which ranged from 380 kPa to 1200 kPa. Figure 5.9 shows the predicted versus measured fuel consumption at the same drawbar power. The comparison for a typical field in one gear is shown in Figure 5.10.

Table 5.4 shows the relative error of the prediction, mean difference in predicted minus measured fuel consumption and the standard deviation of mean difference. One of the possible sources of the variation in comparison may be the variation of the heat value of the fuel used.

From Table 5.4 and Figure 5.9, the predicted fuel consumption is in reasonable good agreement with the measured drawbar fuel consumption.

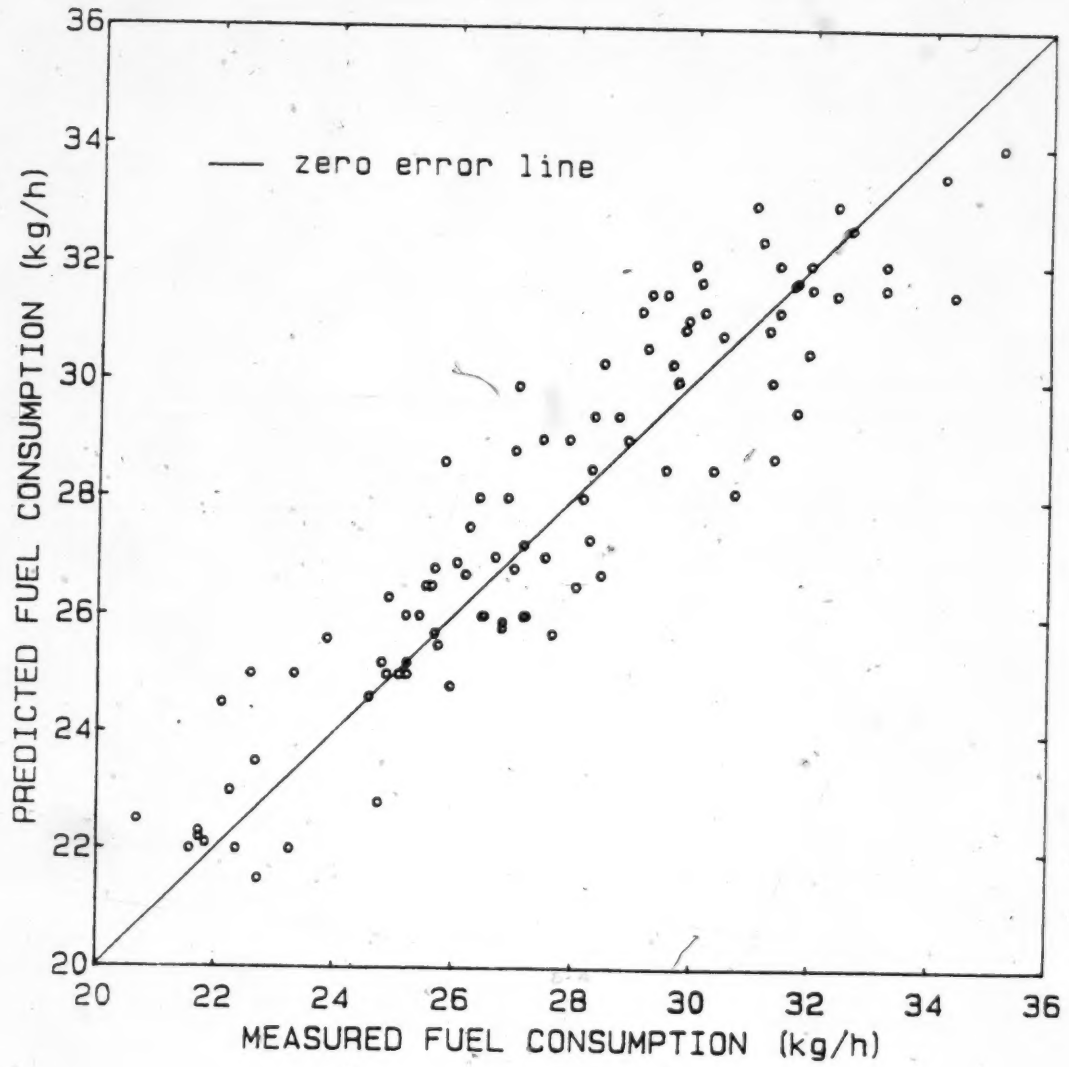


Figure 5.9 Comparison of predicted versus measured tractor fuel consumption

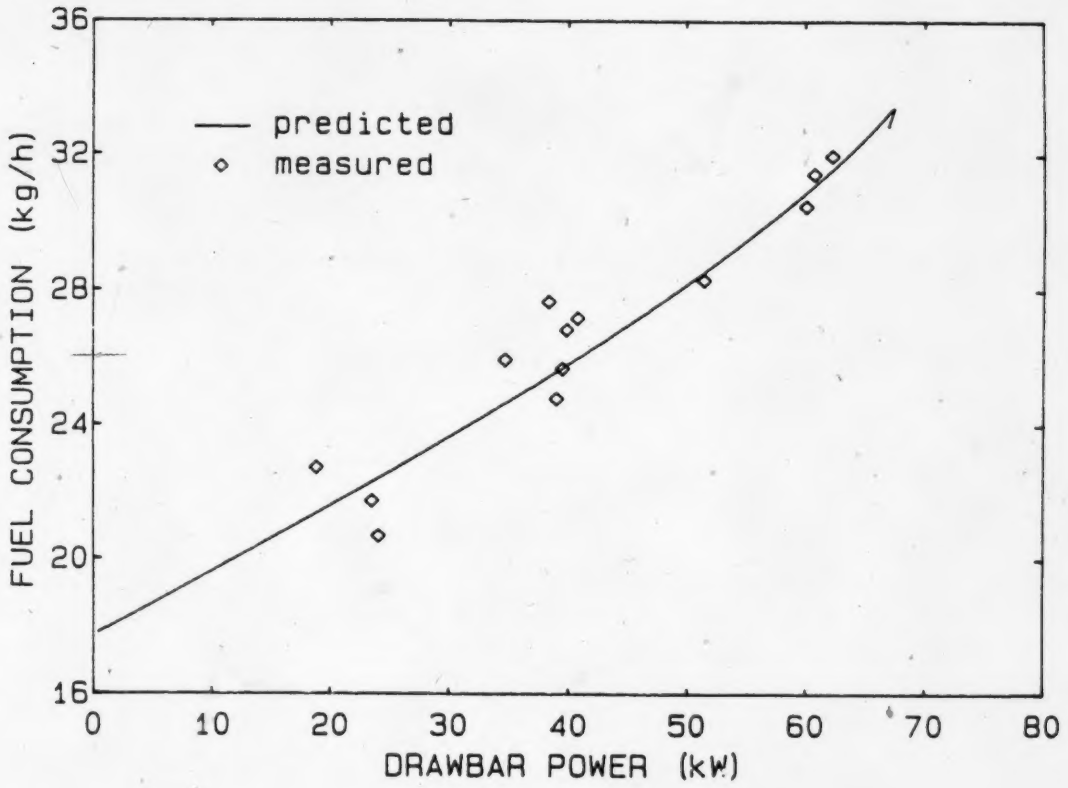


Figure 5.10 Comparison of predicted and measured fuel consumption versus drawbar power for a typical field

Table 5.4 Statistical comparison of predicted and measured fuel consumption

Relative error (%)	mean difference (kg/h)	Standard deviation of mean difference (kg/h)	95% confidence interval estimate of true mean difference (kg/h)
4	0.22	0.13	$-0.04 \leq \mu_d \leq 0.46$

5.3 Predicted Versus Measured Tractor-Implement Performance

The predicted and measured tractor-cultivator performance was compared. For the comparison the tractor was run in tenth gear at full throttle setting and ballast of 2177 kg. Verification for summer fallow fields and for stubble fields were made separately since the draft equations were different. The input of the soil strength was cone index only. For summer fallow conditions, three fields, the cone index of which ranged from 385 kPa to 540 kPa, were selected. For three stubble fields, the cone index ranged from 870 kPa to 1246 kPa. Figure 5.11 shows the predicted and measured drawbar pull versus tillage depth for the three summer fallow fields. The relative error of the predicted pull is 21%. Figures 5.12 to 5.14 show the predicted and measured drawbar power, slip, and fuel consumption versus depth for the three summer fallow fields. The predicted performance is in acceptable agreement with the measured performance.

The predicted performance for stubble fields, however, was not close to the measured performance. The predicted drawbar pull is much lower than the measured drawbar pull in

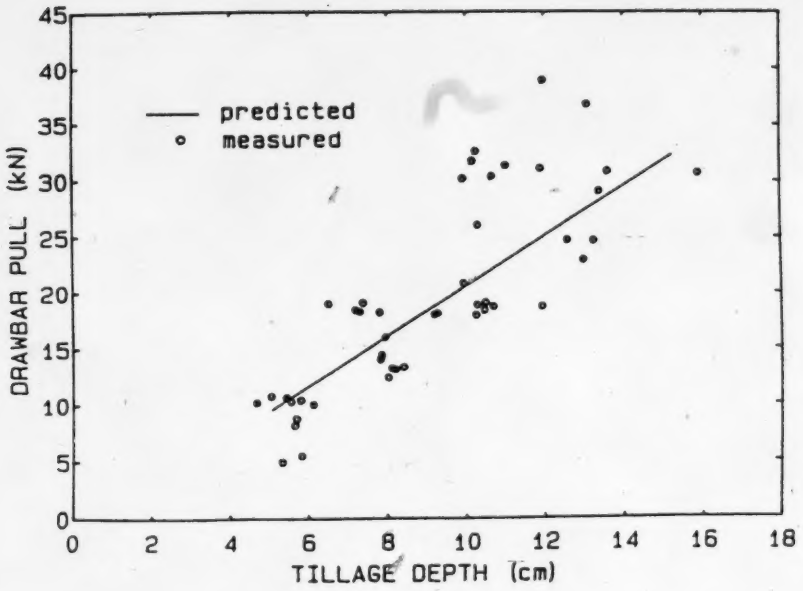


Figure 5.11 Predicted and measured drawbar pull versus tillage depth in three summer fallow fields

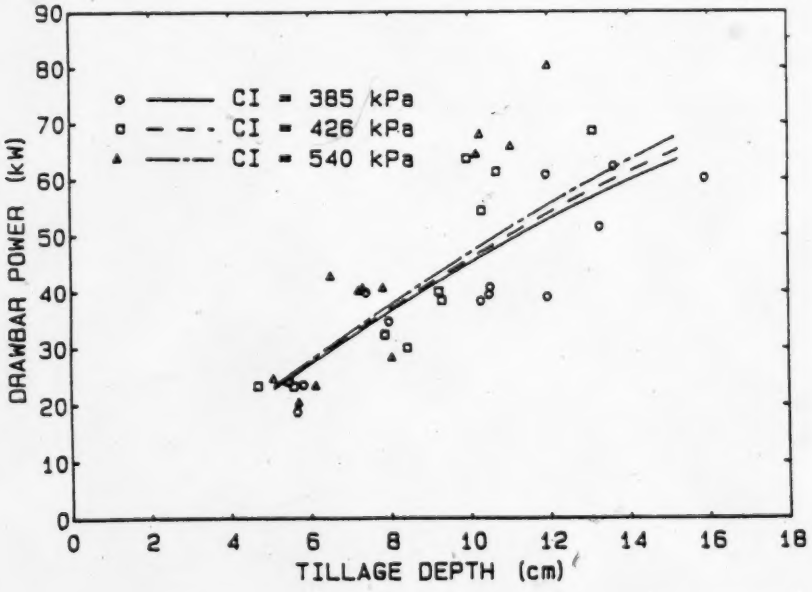


Figure 5.12 Predicted and measured drawbar power versus tillage depth in three summer fallow fields

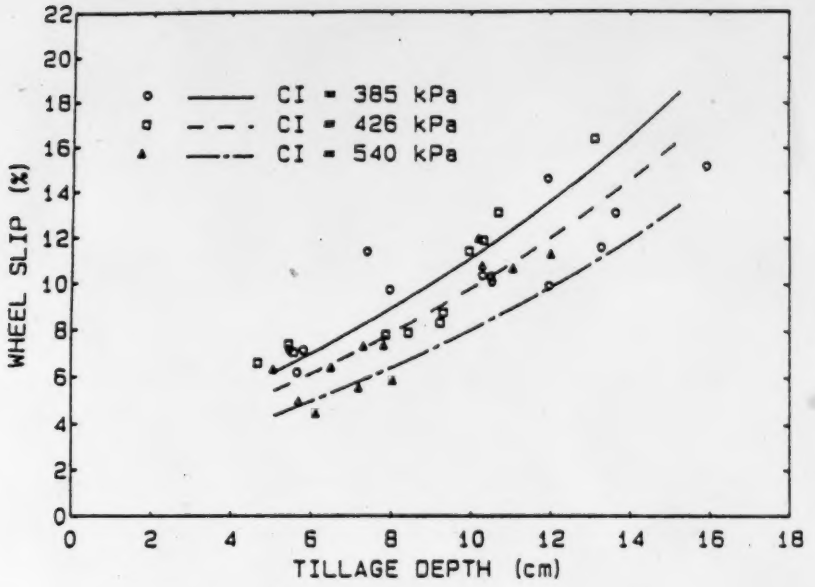


Figure 5.13 Predicted and measured slip versus tillage depth in three summer fallow fields

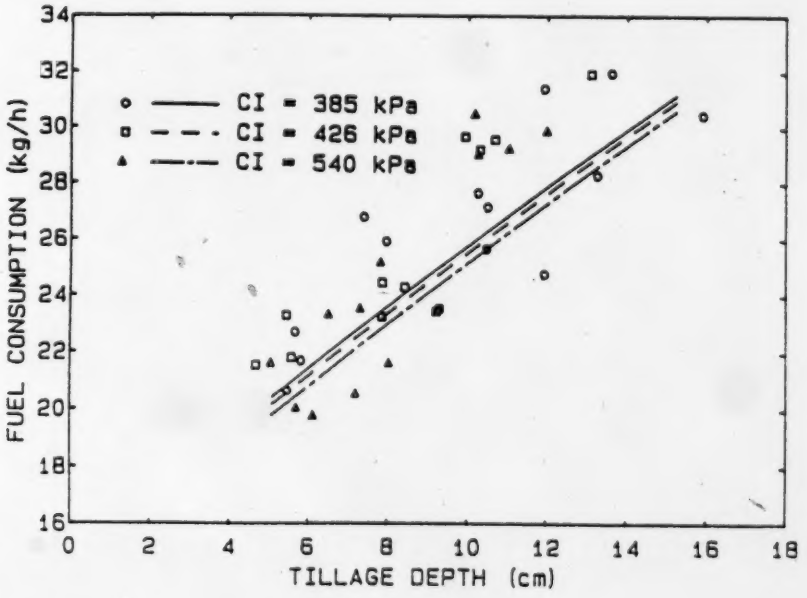


Figure 5.14 Predicted and measured fuel consumption versus tillage depth in three summer fallow fields

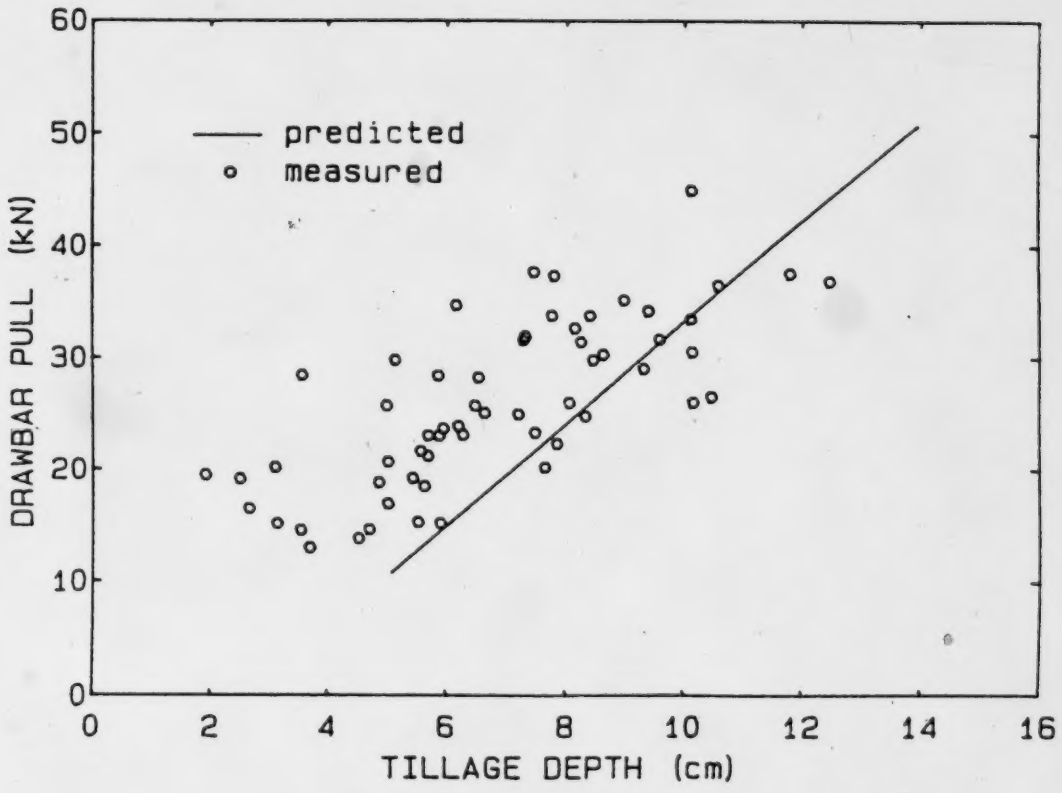


Figure 5.15 Predicted and measured drawbar pull in stubble fields

most of the cases as shown in Figure 5.15. The lower predicted values of slip, drawbar power, and fuel consumption are obviously due to the lower prediction of drawbar pull. A conclusion may be drawn that the draft equation of the cultivator in the model for stubble fields does not adequately describe the draft requirement of the cultivator in the stubble fields related to this study. This is perhaps due to the variation of soil and field conditions.

5.4 Predicted Versus Measured Drawbar Power at Rated Engine Speed

The accuracy of the prediction of drawbar power at or near rated engine speed is very important since tractors working in the field are often operated at or near rated engine speed. The predicted drawbar power at or near rated engine speed was compared with the measured drawbar power at the same engine speed. The comparison was made for different gears, ballast, and soil conditions. The throttle setting was in full or high idle position for all the tests. The predicted versus measured drawbar power at the same engine speed (at or near rated speed) is shown in Figure 5.16.

The scatter of the points may be due to experimental errors, the assumptions in the model which may not be correct, and the variation of heat value of the fuel used. The relative error of the prediction is 8% which is acceptable.

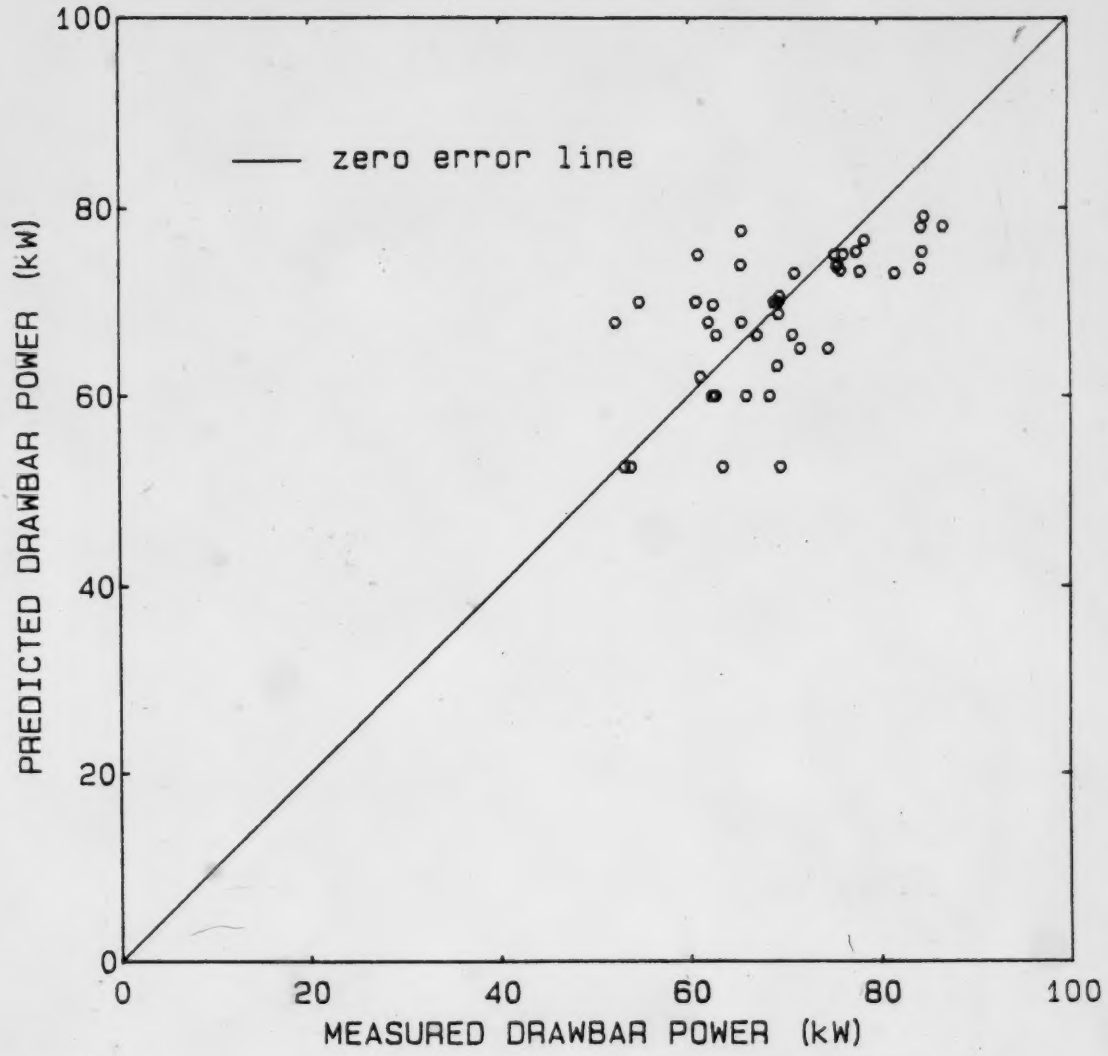


Figure 5.16 Comparison of predicted with measured drawbar power at or near rated engine speed

5.5 Discussion of the Model Performance

The overall model performed properly. This can be seen from the validation of parts of the model. The model is capable of predicting the performance of a two wheel drive, a four wheel drive, or a front wheel assist tractor with dual or single tires. For the tractor-implement combinations the model is capable of predicting the performance of tractor-cultivator, tractor-disk harrow, or tractor-chisel plow combination. Only the model performance for a two wheel tractor with dual tires and for the tractor-cultivator combination have been validated. The validation showed that the predicted performance was reasonably close to the measured performance except for the tractor-cultivator combination in stubble fields. There was no significant difference between prediction from the two approaches although the overall predicted drawbar pull in approach II appeared under-predicted. Therefore, approach I is preferred since only one soil measurement is required.

6. SUMMARY AND CONCLUSIONS

A computer model was developed to predict agricultural tractor performance in the field. The predicted performance of a two wheel drive tractor with dual tires was validated in terms of drawbar pull, drawbar power, and fuel consumption.

To apply the Wismer and Luth equations to dual tires, modification of the equations was necessary. Dual tires modeled as two separate wheels each carrying one half of the load could not closely describe the actual dual tire performance except in soft soils. An equivalent width of dual tires was introduced to apply the Wismer and Luth equations to dual tires in this study. The equivalent width was found to be a function of soil cone index.

The tractive performance was predicted by two approaches. The predicted performance of both approaches for a two wheel drive tractor with dual tires was compared in terms of drawbar pull and drawbar power at the same slip based on the measured performance. The difference of the results of the two approaches was not significant. Therefore, approach I requiring only one soil measurement is preferred.

The predicted tractive performance was compared with the measured tractive performance in terms of drawbar pull and drawbar power at the same slip. A reasonably good agreement between predicted and measured tractive performance was obtained. The comparison of the predicted

with measured drawbar performance showed considerable variation. This was expected since the soil conditions varied throughout the test fields. The predicted drawbar power at rated engine speed was acceptable in terms of accuracy despite the scatter of the points.

The fuel consumption portion of the model was based on PTO power. The PTO power in the model was obtained by dividing the axle power by 0.96 and the axle power was calculated from the drawbar performance. Therefore, drawbar performance influenced the fuel consumption. The comparison showed the predicted drawbar fuel consumption was in good agreement with the measured drawbar fuel consumption.

The accuracy of the predicted performance for tractor-implement combination was dependent on the accuracy of the draft prediction equation of the implements. The predicted performance for the tractor-cultivator combination in summer fallow fields was close to the measured performance. In stubble fields, however, the predicted performance was unacceptable.

The accuracy of the model prediction can be influenced greatly by the input of soil properties and field conditions. The model was only capable of predicting tractor performance in typical field conditions. The 0-150 mm cone index was the average cone index input to the model. The soil shear properties measured by the shear meter used in this study were generally good. For several fields the measured values were lower than they should be. The soil

deformation modulus at or near the estimated contact pressure between wheel and soil was the best input soil deformation modulus for dual tires.

The prediction of the overall model in terms of estimating the tractor performance in the field and determining the trends was within acceptable limits.

7. RECOMMENDATIONS FOR FUTURE WORK

The following suggestions are made for future work based on the results obtained in this study.

1. The model requires further verification for a two wheel drive tractor with single tires and a four wheel drive tractor with single and dual tires.
2. More draft requirement information of implements is needed to extend the model for other types of implements and to improve the accuracy of the prediction for tractor implement combinations in tillage operations. Effects of soil type on draft requirements of implements should be considered in order to improve the accuracy of the prediction.
3. To use the model as a simulator of the tractor and tractor-implement combination performance in the field, the computer model should be improved in term of programming techniques to enhance user friendliness.

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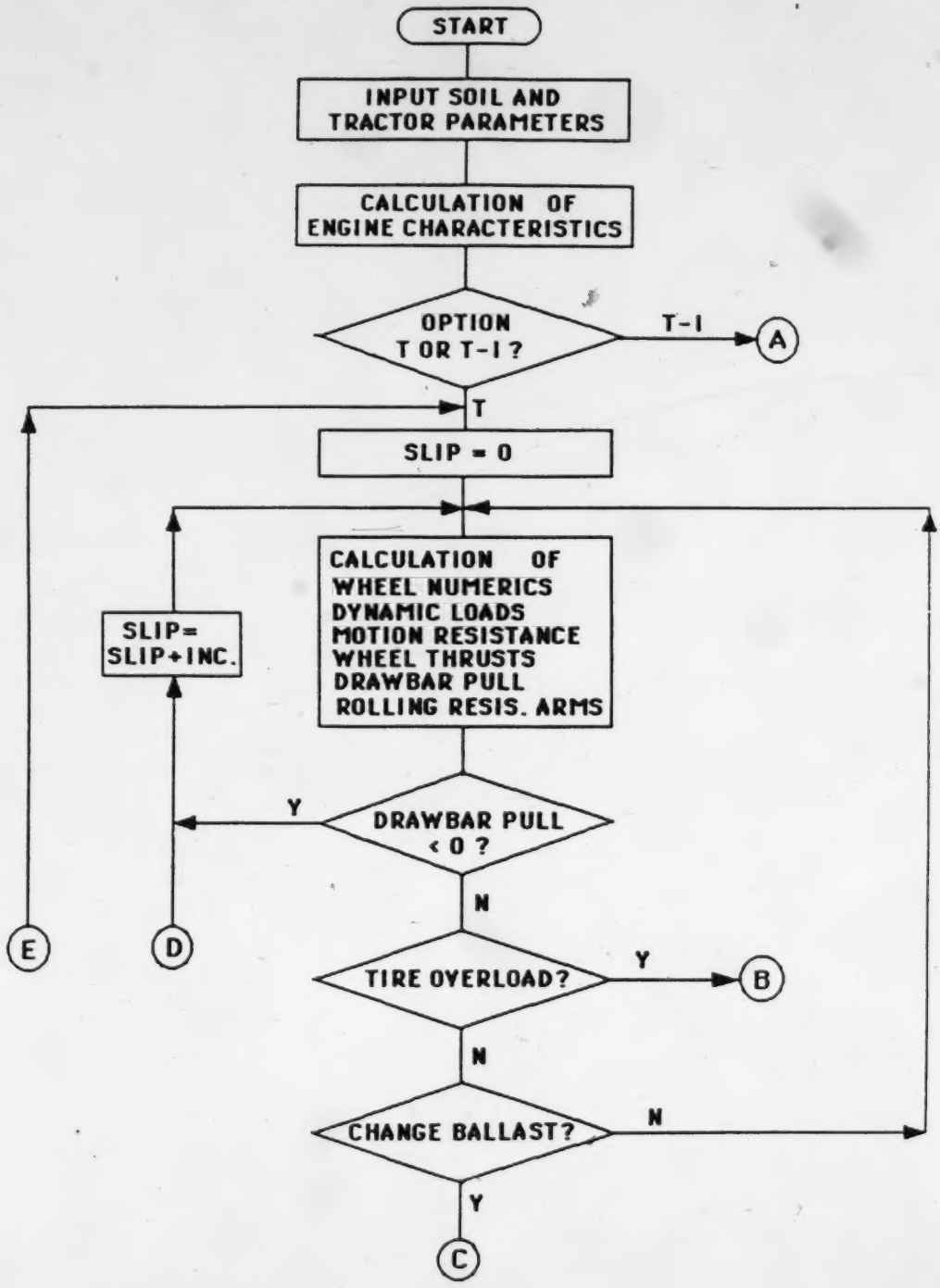
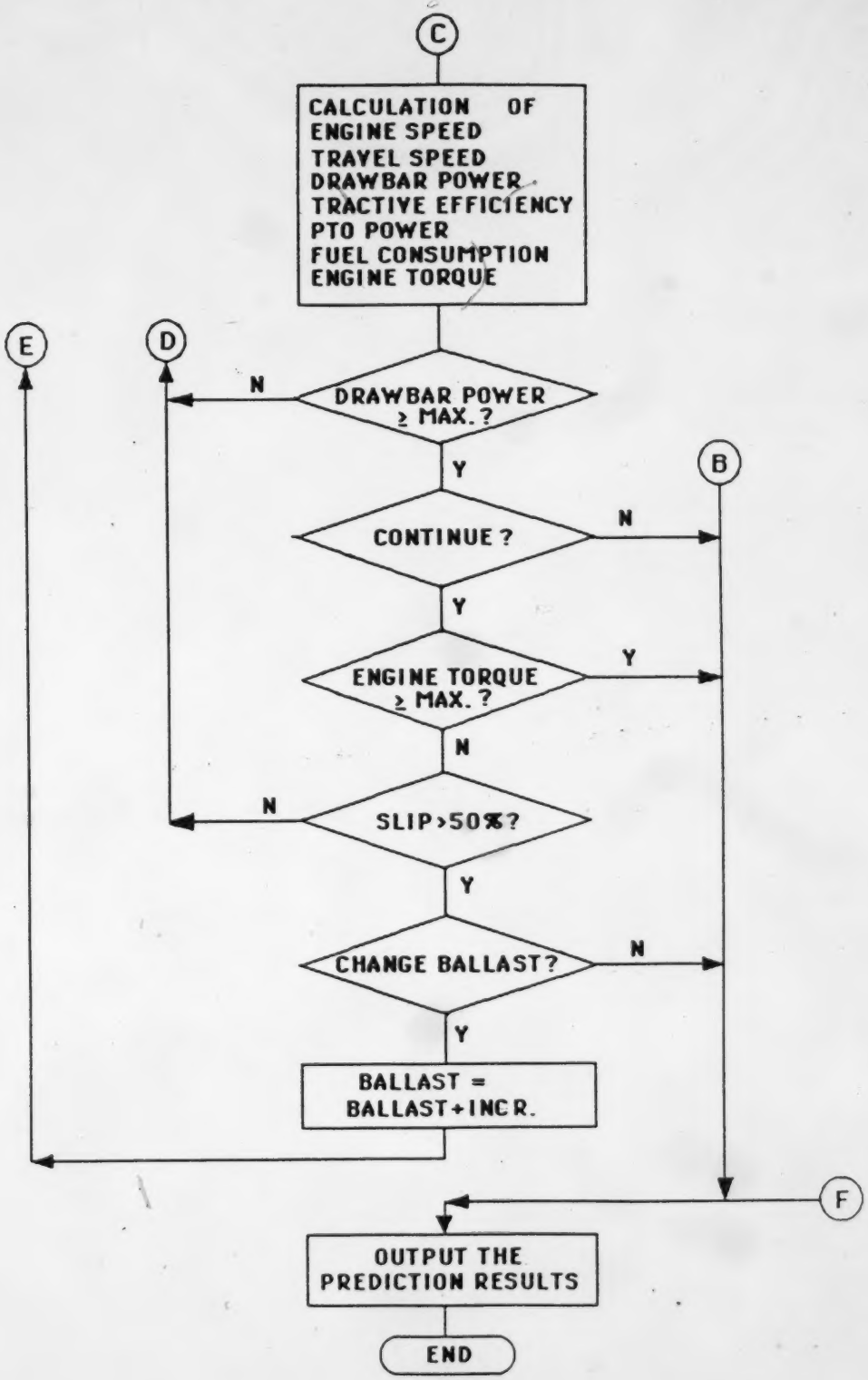
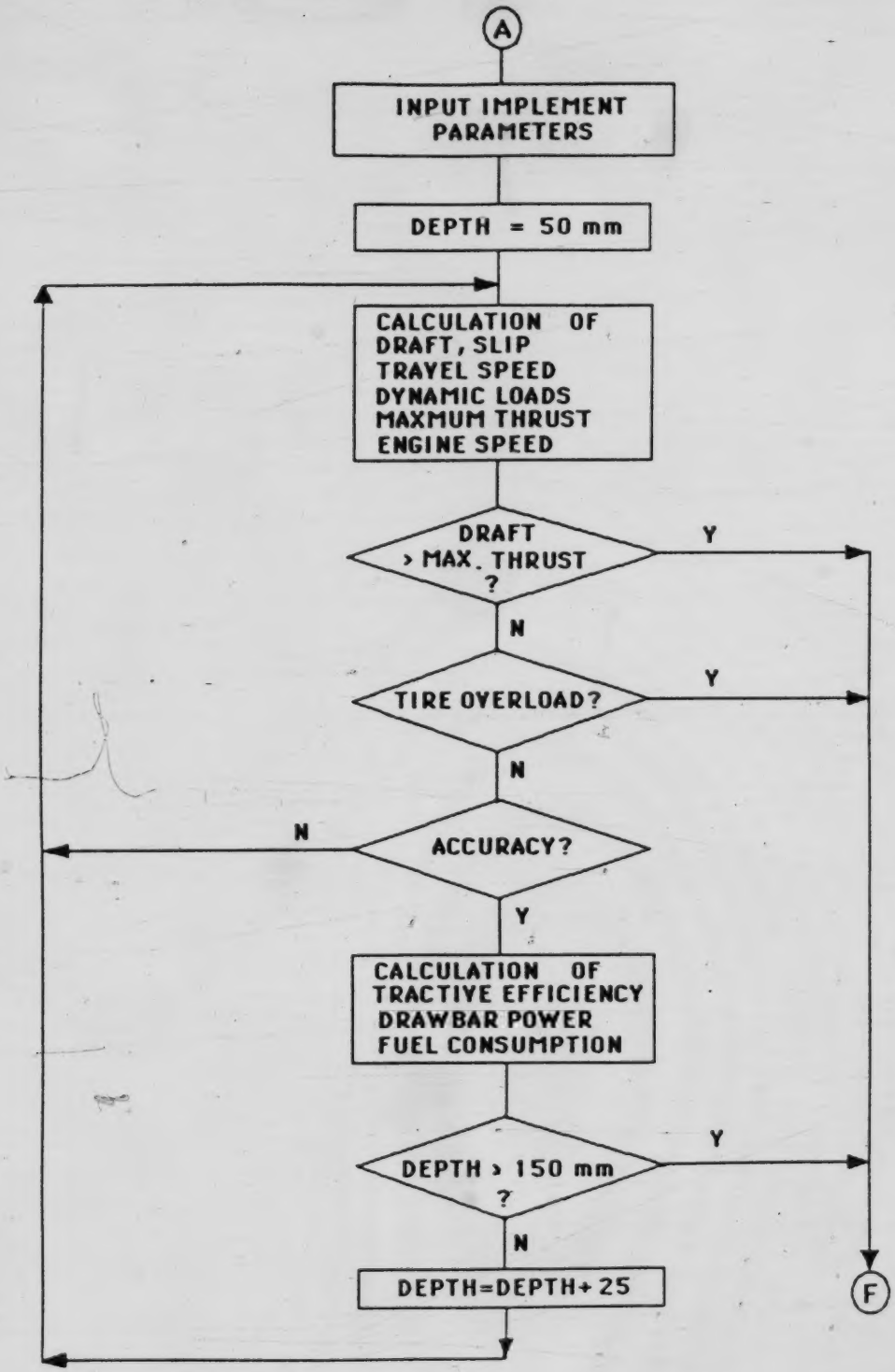
APPENDIX A.1: FLOWCHART OF THE COMPUTER MODEL




C
CALCULATION OF
ENGINE SPEED
TRAVEL SPEED
DRAWBAR POWER
TRACTIVE EFFICIENCY
PTO POWER
FUEL CONSUMPTION
ENGINE TORQUE
E
D
DRAWBAR POWER
≥ MAX.?
N
Y
B
CONTINUE?
N
Y
ENGINE TORQUE
≥ MAX.?
Y
N
SLIP>50%?
N
Y
CHANGE BALLAST?
N
Y
BALLAST =
BALLAST+INCR.
F
OUTPUT THE
PREDICTION RESULTS
END


A
INPUT IMPLEMENT PARAMETERS
DEPTH = 50 mm
CALCULATION OF DRAFT, SLIP TRAVEL SPEED DYNAMIC LOADS MAXMUM THRUST ENGINE SPEED
DRAFT > MAX. THRUST ?
Y
N
TIRE OVERLOAD?
Y
N
ACCURACY?
N
Y
CALCULATION OF TRACTIVE EFFICIENCY DRAWBAR POWER FUEL CONSUMPTION
DEPTH > 150 mm ?
Y
N
DEPTH=DEPTH+25
F

APPENDIX A.2: PROGRAM LISTING

```
10   '  ************************************************************************
20   '  *                                                                      *
30   '  *                          PROGRAM  PTRPF                              *
40   '  *                        FOR THESIS PROJECT                            *
50   '  *                              BY                                      *
60   '  *                           ZHAOWEI WANG                               *
70   '  *                           SUPERVISED BY                              *
80   '  *                          Dr. K. W. DOMIER                            *
90   '  *                          ================                            *
100  '  *                 DEPARTMENT OF AGRICULTURAL ENGINEERING               *
110  '  *                         UNIVERSITY OF ALBERTA                        *
120  '  *                                                                      *
130  '  ************************************************************************
140  '
150  ' PURPOSE: TO PREDICT THE AGRICULTURAL TRACTOR PERFORMANCE IN THE FIELD
160  ' ======================================================================
170  ' THIS IS A COMPUTER MODEL WHICH PREDICTS THE TRACTOR PERFORMANCE IN
180  ' THE FIELD. THE PROGRAM IS CAPABLE OF PREDICTING A TWO WHEEL DRIVE, A
190  ' FOUR WHEEL DRIVE, OR A FRONT WHEEL ASSIST TRACTOR PERFORMANCE IN THE
200  ' FIELD. THE PROGRAM ALSO HAS THE CAPABILITY OF SIMULATING
210  ' TRACTOR-CULTIVATOR, TRACTOR-DISK HARROW, OR TRACTOR-CHISEL PLOW
220  ' COMBINATION PERFORMANCE.
230  ' ======================================================================
740  '
750  ' ******* MAIN SECTION *******
755  '
790  DEF FNFUEL(PP)=(3.6*PP+CONSTC*DISPM*ENSP^2/(2*16670000#))/(NHV*CONSTA)
830  DIM SLIP(100),TREFF(100),DRPL(100),TVSPD(100),RDYLD(100),FDYLD(100),TEMP(9),DRPOW(100)
840  DIM CNF(100),CNR(100),FRRSTN(100),THRUST(100),FRARM(100),RRARM(100),PLWLRATIO(100)
850  DIM WTRSF(100),FUELCP(100),ENSP(100),ATRVSP(100),IDEPTH(100)
910  GOSUB 1010
920  ON VAL(A$) GOSUB 1117, 1310
922  PRINT "TRACTOR PERFORMANCE ONLY OR TRACTOR IMPLEMENT COMBINATION(T/I)?";
924  I$=INKEY$:IF I$="" THEN GOTO 924 ELSE PRINT I$:IF I$="I" OR I$="i" THEN GOTO 930
```

```
925 PRINT "DO YOU WANT THE PREDICTION BASED ON CONE INDEX ONLY OR BASED ON CONE INDEX AND
SHEAR COMBINATION(C/S)?";
927 CHOICE$=INKEY$:IF CHOICE$="" THEN GOTO 927 ELSE PRINT CHOICE$
930 GOSUB 2000
935 GOSUB 2280
936 IF (I$="i" OR I$="I") AND (DVOPT$="TWD" OR DVOPT$="twd") THEN GOSUB 6950:GOTO 960
938 IF (I$="i" OR I$="I") AND (DVOPT$="FWD" OR DVOPT$="fwd" OR DVOPT$="fwa" OR
DVOPT$="FWA") THEN GOSUB 7500:GOTO 960
940 IF DVOPT$="TWD" OR DVOPT$="twd" THEN GOSUB 3000
950 IF DVOPT$="FWD" OR DVOPT$="fwd" OR DVOPT$="FWA" OR DVOPT$="fwa" THEN GOSUB 4500
960 IF DVOPT$ <> "TWD" AND DVOPT$<>"twd" AND DVOPT$<>"FWD" AND DVOPT$<>"fwd" AND
DVOPT$<>"FWA" AND DVOPT$<>"fwa" THEN PRINT "Check your tractor type input please":GOTO 910
970 GOSUB 6000
975 END
980 '
1010 CLS:LOCATE 5,1: PRINT " ****** MODEL INPUT PARAMETERS ******"
1015 '
1020 PRINT:PRINT "Engine & Tractor:"
1030 PRINT "Maximum engine speed, Engine Speed-PTO Power relationship, Rated engine
speed."
1035 PRINT "Engine speed ,Fuel consumption, and PTO power at 85% and 21.3% load."
1038 PRINT "Net heat value of fuel and engine displacement."
1040 PRINT "Max. PTO Power, Gear No.,No slip travel speed, Tractor rear static axle weight
and ballast,"
1050 PRINT "Tractor front static axle weight and ballast, Drawbar height, Wheel base."
1060 PRINT:PRINT "Tire:"
1070 PRINT "Unloaded tire sizes (diameter, width), Inflation pressures"
1080 PRINT "Tire max. load limit and dual or single wheels."
1090 PRINT:PRINT "Soil:"
1100 PRINT "Soil type, Soil cone index, Soil internal friction angle & cohesion"
1107 PRINT "The input parameters can be either inputed from key board or read"
1109 PRINT "from a file. Enter your choice (1--keyboard or 2--file):";
1111 A$=INKEY$:IF A$="" THEN GOTO 1111 ELSE PRINT A$
1113 IF A$ <> "1" AND A$ <> "2" THEN:BEEP:PRINT A$;"is an invalid choice please repeat;
enter 1 or 2.":GOTO 1107 ELSE RETURN
1114 '
```

```
1115 ' ******** INPUT FROM KEYBOARD ********
1116 '
1117 INPUT "Field number";FLDNUM$
1118 INPUT "Operation Date";OPDATE$
1119 INPUT "Tractor name";TNAME$
1120 INPUT "Engine speed (rpm)";ENSP1
1130 INPUT "Engine maxmum speed (rpm)";MENSP
1140 INPUT "Rated engine speed (rpm)";RENSP
1150 INPUT "Engine speed-PTO power curve (6 pairs of points, rpm,kW)";S(1),P(1),S(2),
P(2),S(3),P(3),S(4),P(4),S(5),P(5),S(6),P(6)
1160 INPUT "Gear No. & no load travel speed (km/h)";GN,TVSP
1165 INPUT "Rear tire size and Front tire size";RTSIZE$,FTSIZE$
1170 INPUT "Rated PTO power (kW)";RPTOP
1180 INPUT "Rear static axle weight (kg)";RSAW
1190 INPUT "Front static axle weight (kg)";FSAW
1195 INPUT "Rear ballast (kg)and Front ballast (kg)";RBALAS,FBALAS
1200 INPUT "Drawbar height (m)";DRHT
1210 INPUT "Wheel base (m)";WHBS
1220 INPUT "Two-wheel(TWD) or Four wheel(FWD) or Front wheel Assist(FWA)";DVOPT$
1225 INPUT "Dual or single wheels";DUORSGL$
1230 INPUT "Rear Tire diameter & width(m)";RTDIA,RTWID
1235 INPUT "Front Tire diameter & width(m)";FTDIA,FTWID
1240 INPUT "Inflation pressures(front,rear,psi)";FINPR,RINPR
1250 INPUT "Maxmum tire load limits ( front, rear, kg)";FTMLL,RTMLL
1260 INPUT "Soil type";SLTP$
1270 INPUT "Soil strength-- Cone index(front,rear,kPa)";CONI,RCONI
1272 INPUT "Soil internal friction angle (deg) and cohesion (kPa)";IFAL,COHN
1273 INPUT "Soil moisture content(%)";MOCT
1275 INPUT "Engine Speed at 85% Load (rpm)";ENSP85
1280 INPUT "Engine Speed at 21.3% Load (rpm)";ENSP21
1285 INPUT "85% PTO Power (kW)";PTOHP85
1287 INPUT "21.3% PTO Power (kW)";PTOHP21
1290 INPUT "Fuel Consumption at 85% Load (kg/h)";FUEL85
1292 INPUT "Engine Displacement (cm³)";DISPM
1295 INPUT "Fuel Net Heat Value (kJ/kg)";NHV
1305 RETURN
```

```
1306 '
1307 ' ******* INPUT FROM A FILE *******
1308 '
1310 OPEN "IPDT" FOR INPUT AS #1
1320 INPUT #1,ENSP1,RENSP,RPTOP,GN,TVSP,RSAW
1330 INPUT #1,S(1),P(1),S(2),P(2),S(3),P(3)
1340 INPUT #1,S(4),P(4),S(5),P(5),S(6),P(6)
1345 INPUT #1,FSAW,DRHT,WHBS,MENSP,FTMLL,RCONI
1348 INPUT #1,TNAME$,RTSIZE$,FTSIZE$
1351 INPUT #1,DVOPT$
1355 INPUT #1,SLTP$
1357 INPUT #1,DUORSGL$
1358 INPUT #1,FLDNUM$
1360 INPUT #1,OPDATE$
1365 INPUT #1,RTDIA,RTWID,FTDIA,FTWID,RINPR,RTMLL
1370 INPUT #1,CONI,IFAL,COHN,MOCT,CONSTK,FINPR
1372 INPUT #1,NHV,PTOHP85,PTOHP21,DISPM,ENSP85,ENSP21
1373 INPUT #1,FUEL85,FUEL21,RBALAS,FBALAS
1375 IF EOF(1) THEN CLOSE
1400 PRINT "S(1)","P(1)","S(2)","P(2)","S(3)"
1410 PRINT S(1),P(1),S(2),P(2),S(3)
1420 PRINT "P(3)","S(4)","P(4)","S(5)","P(5)"
1430 PRINT P(3),S(4),P(4),S(5),P(5)
1440 PRINT " S(6)"," P(6)"," RSAW"," RTMLL","DUORSGL"
1450 PRINT S(6),P(6),RSAW,RTMLL,DUORSGL$
1455 PRINT "ENSP1","RENSP","RPTOP","GN","TVSP"
1460 PRINT ENSP1,RENSP,RPTOP,GN,TVSP
1470 PRINT "FSAW","DRHT","WHBS","DVOPT","SLTP"
1475 PRINT FSAW,DRHT,WHBS,DVOPT$,SLTP$
1480 PRINT "RTDIA","RTWID","FTDIA","FTWID","RINPR"
1485 PRINT RTDIA,RTWID,FTDIA,FTWID,RINPR
1490 PRINT "CONI","IFAL","COHN","MOCT","DRDES"
1495 PRINT CONI,IFAL,COHN,MOCT,DRDES
1500 PRINT "MENSP","FINPR","FTMLL","RCONI","RBALAS"
1510 PRINT MENSP,FINPR,FTMLL,RCONI,RBALAS
1515 PRINT "NHV","PTOHP85","PTOHP21","DISPM","FBALAS"
```

```
1516 PRINT NHV,PTOHP85,PTOHP21,DISPM,FBALAS
1517 PRINT "ENSP85","ENSP21","FUEL85","FUEL21"
1518 PRINT ENSP85,ENSP21,FUEL85,FUEL21
1520 COLOR 15:PRINT:PRINT " CHECK THE INPUT PARAMETERS PLEASE. DO YOU WANT TO CONTINUE
(Y/N)? ";
1530 B$=INKEY$:IF B$="" THEN GOTO 1530 ELSE PRINT B$
1540 IF B$="N" OR B$="n" THEN END
1550 IF B$<>"y" AND B$<>"Y" AND B$<>"n" AND B$<>"N" THEN:BEEP:GOTO 1520 ELSE RETURN
2565 '
2000 ' ****** Initialization of variables ******
2001 '
2002 PI=3.14159 :FCASTIF=2 :RCASTIF=4:SLIP=0:M=0:CONST=1!
2003 IF DVOPT$="FWD" OR DVOPT$="fwd" THEN FCASTIF=RCASTIF
2004 IF I$="I" OR I$="i" THEN INPUT "IMPLEMENT TYPE (CHIESL PLOUGH,CULTIVATOR, BLADE
CULTIVATOR,ONE WAY DISK HARROW,TANDEM DISK HARROW)";IMTYPE$:INPUT "IMPLEMENT WIDTH AND
DEPTH(m,inches)";IMWID,IDEPTH
2005 IF (I$="i" OR I$="I") AND (IMTYPE$="TANDEM DISK HARROW" OR IMTYPE$="tandem disk
harrow") THEN INPUT "DISK ANGLE(deg.)";ANL
2006 IF (I$="I" OR I$="i") AND (IMTYPE$="CHIESL PLOUGH" OR IMTYPE$="chiesl plough") THEN
INPUT "TILLAGE TYPE(HEAVY OR LIGHT PRIMARY)";SSCON1$
2007 IF (I$="i" OR I$="I") AND (IMTYPE$="CULTIVATOR" OR IMTYPE$="cultivator") THEN INPUT
"TILLAGE TYPE(HEAVY OR LIGHT PRIMARY,HEAVY OR LIGHT SECONDARY)";SSCON2$
2008 IF (I$="I" OR I$="i") AND (IMTYPE$="BLADE CULTIVATOR" OR IMTYPE$= "blade cultivator")
THEN INPUT "TILLAGE TYPE (PRIMARY,SECONDARY)";SSCON3$
2009 IF (I$="i" OR I$="I") THEN INPUT "ARE YOU GOING TO GO THROUGH FROM 2 TO 6 INCHES
DEPTH(Y/N)";DP$
2010 ' ***** Calculation of Engine Speed-Torque relationship *****
2011 '
2012 CLS:LOCATE 10,5:COLOR 31:PRINT "$$$$ THE PROGRAM IS RUNNING, THANK YOU FOR NOT
SWITCHING IT OFF $$$$":COLOR 7
2015 '
2020 FOR I=1 TO 6
2030 TEMP(I)=P(I)*1000/.87
2040 T(I)=TEMP(I)*60/(2*PI*S(I))
2050 NEXT I
2060 ENSP=ENSP1-(MENSP-RENSP)
```

```
2070 GOSUB 5300:TOQU2=TOQU:ENSP2=ENSP
2080 '
2090 ENSP=RENSP:GOSUB 5300:TOQUO=TOQU
2100 ENSP=ENSP-20
2110 GOSUB 5300:TOQUN=TOQU
2120 IF TOQUN < TOQUO THEN ENSP3=ENSP-10:TOQU3=(TOQUO+TOQUN)/2:GOTO 2150
2130 TOQUO=TOQUN
2140 GOTO 2100
2150 '
2205 '
2210 ' ****** Calculation of the gear ratio between engine and axle *****
2215 '
2220 EARA=(RSAW+RBALAS)*9.8/(2*(RINPR+RCASTIF)*6895):LENTH=EARA/RTWID
2225 DEFL=EARA/(PI*(RTDIA*RTWID)^.5)
2230 IF DUORSGL$="DUAL" OR DUORSGL$="dual" THEN DEFL=DEFL/2:LENTH=LENTH/2
2240 LRADI=RTDIA/2-DEFL
2245 ERRADI=LRADI+DEFL/2
2250 WHESP=TVSP*1000/(3600*ERRADI)
2260 GRATIO=MENSP*2*PI/(WHESP*60)
2270 RETURN
2280 '
2290 PMEP85=2*60000000#*PTOHP85/(DISPM*ENSP85)
2300 PMEP21=2*60000000#*PTOHP21/(DISPM*ENSP21)
2301 FUEL85=FUEL85*PTOHP85:FUEL21=FUEL21*PTOHP21
2302 BATA85=2*NHV*FUEL85*1000000!/(60*ENSP85*DISPM)
2305 BATA21=2*NHV*FUEL21*1000000!/(60*ENSP21*DISPM)
2310 CONSTA=(PMEP85-PMEP21)/(1!*(BATA85-BATA21))
2320 CONSTB=1!*BATA85*CONSTA-PMEP85
2340 CONSTC=1000*CONSTB/ENSP
2350 RETURN
3000 '
3010 ' ****** Two Wheel Drive Tractor *******
3011 '
3030 SLIP=9.999999E-06:M=0:OPTEST$="FALSE":OP$="FALSE"
3090 RDYLDO=RSAW+RBALAS:FDYLDO=FSAW:CNFO=0:CNRO=0:FRRSTO=0:THRUSTO=0:FRARMO=0
3095 MAX=100:DRPLO=0:RRARMO=0
```

```
3096 '
3100 WHILE MAX > .015
3110 RDYLDN=((RSAW+RBALAS)*9.8*WHBS+FDYLDO*FRARMO+DRPLO*DRHT)/(WHBS-RRARMO)
3120 FDYLDN=(FSAW*9.8*WHBS-RDYLDN*RRARMO-DRPLO*DRHT)/(WHBS+FRARMO)
3130 CNFN=CONI*1000*FTWID*FTDIA*2/FDYLDN
3140 CNRN=CONI*1000*RTWID*RTDIA*2/RDYLDN
3142 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND CONI<447 THEN CNRN=2*CNRN
3144 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND CONI>447 AND CONI<1113 THEN
CNRN=(-.0015*CONI+2.6729)*CNRN
3150 FRRSTN=FDYLDN*(1.2/CNFN+.04)
3155 IF CHOICE$="S" OR CHOICE$="s" THEN THRUSTN=(2*EARA*COHN*1000+RDYLDN*TAN(IFAL*PI/180))
*(1+EXP(-SLIP*LENTH/CONSTK)*CONSTK/(SLIP*LENTH)-CONSTK/(SLIP*LENTH))
-RDYLDN*(1.2/CNRN+.04):GOTO 3170
3160 THRUSTN=.75*RDYLDN*(1-EXP(-.3*CNRN*SLIP))-RDYLDN*(1.2/CNRN+.04)
3170 FRARMN=(1.2/CNFN+.04)*FTDIA/2
3180 RRARMN=(1.2/CNRN+.04)*RTDIA/2
3190 DRPLN=THRUSTN-FRRSTN
3195 IF DRPLN < 0 THEN SLIP=SLIP+.001:GOTO 3110
3200 TEMP(1)=RDYLDN-RDYLDO
3210 TEMP(2)=FDYLDN-FDYLDO
3220 TEMP(3)=CNFN-CNFO
3230 TEMP(4)=CNRN-CNRO
3240 TEMP(5)=FRRSTN-FRRSTO
3250 TEMP(6)=THRUSTN-THRUSTO
3260 TEMP(7)=FRARMN-FRARMO
3270 TEMP(8)=RRARMN-RRARMO
3280 TEMP(9)=DRPLN-DRPLO
3290 MAX=ABS(TEMP(1))
3300 FOR K=2 TO 9
3310 IF ABS(TEMP(K)) > MAX THEN MAX=ABS(TEMP(K))
3320 NEXT K
3330 RDYLDO=RDYLDN:FDYLDO=FDYLDN:CNFO=CNFN:CNRO=CNRN:FRRSTO=FRRSTN
3335 THRUSTO=THRUSTN:FRARMO=FRARMN:RRARMO=RRARMN:DRPLO=DRPLN:IF DVOPT$="FWD" OR
DVOPT$="fwd" OR DVOPT$="fwa" OR DVOPT$="FWA" OR I$="i" OR I$="I" THEN RETURN
3340 WEND
3345 '
```

```
3350 EARA=RDYLDN/(2*(RINPR+RCASTIF)*6895):LENTH=EARA/RTWID
3355 DEFL=EARA/(PI*(RTDIA*RTWID)^.5)
3360 IF DUORSGL$="DUAL" OR DUORSGL$="dual" THEN LENTH=LENTH/2:DEFL=DEFL/2
3370 FDEFL=CONST*DEFL
3380 LRADI=RTDIA/2-FDEFL
3390 '
3395 IF CHOICE$="S" OR CHOICE$="s" THEN TORQUE=LRADI*(THRUSTN+RDYLDN* (1.2/CNRN+.04))
/(GRATIO*.8):GOTO 3410
3400 TORQUE=.75*LRADI*RDYLDN*(1-EXP(-.3*CNRN*SLIP))/(GRATIO*.8)
3410 '
3484 IF ENSP2 > ENSP3 THEN IF TORQUE <= TOQU2 THEN ENSP=ENSP1-TORQUE* (MENSP-RENSP) /TOQU2
ELSE ENSP=ENSP2-(ENSP2-ENSP3)*(TORQUE-TOQU2)/(TOQU3-TOQU2)
3490 IF ENSP2<= ENSP3 THEN ENSP=ENSP1-TORQUE*(MENSP-RENSP)/TOQU2:TOQU3=TOQU2
3500 IF (TOQU3-TORQUE)<0 THEN SLIP=SLIP-SLIP/100:GOTO 3090
3510 ERRADI=LRADI+FDEFL/3
3520 TTVSP=ENSP*2*PI/(GRATIO*60)*ERRADI
3530 ATRVSP=TTVSP*(1-SLIP)
3540 DRPOW=DRPLN*ATRVSP
3545 IF CHOICE$="S" OR CHOICE$="s" THEN TREFF=(DRPLN/(THRUSTN+RDYLDN*(1.2/CNRN+.04)))
*(1-SLIP):GOTO 3560
3550 TREFF=(1-((1.2/CNRN+.04)+FDYLDN/RDYLDN*(1.2/CNFN+.04))/(.75*(1-EXP(-.3*
CNRN*SLIP))))*(1-SLIP)
3560 AXLPOW=TORQUE*GRATIO*.87*TTVSP/ERRADI
3570 PTOPOW=AXLPOW/.96
3675 M=M+1
3680 DRPOW(M)=DRPOW/1000:TREFF(M)=TREFF
3685 FUELCP(M)=FNFUEL(PTOPOW)
3700 WTRSF(M)=RDYLDN-(RSAW+RBALAS)*9.8
3720 RDYLD(M)=RDYLDN
3730 FDYLD(M)=FDYLDN
3740 CNF(M)=CNFN:CNR(M)=CNRN
3750 FRRSTN(M)=FRRSTN
3760 THRUST(M)=THRUSTN
3780 FRARM(M)=FRARMN
3790 RRARM(M)=RRARMN
3795 ENSP(M)=ENSP
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```
3797 ATRVSP(M)=ATRVSP
3800 DRPL(M)=DRPLN/1000
3802 PLWLRO=THRUSTN/RDYLDN
3808 SLIP(M)=SLIP*100:IF CHOICE$="S" OR CHOICE$="s" THEN SLIP(M)=SLIP(M)+1.5
3810 IF DVOPT$="fwd" OR DVOPT$="FWD" OR DVOPT$="fwa" OR DVOPT$="FWA" OR I$="i" OR I$="I"
THEN RETURN
3812 IF OPTEST$="FALSE" AND DRPOW(M) <= DRPOW(M-1) THEN OPSLIP=SLIP-.0025
:OPTEST$="TRUE":OP$="TRUE"
3815 IF WTRSF(M)>=FSAW*9.8 THEN PRINT "THE TRACTOR IS UNSTABLE NOW!!!":INPUT "ENTER THE
BALLAST YOU WANT TO REDUCE: ";INCR:BALAS=BALAS-INCR:GOTO 3010
3825 IF OP$="TRUE" THEN INPUT " THE SLIP HAS REACHED THE OPTIMUM SLIP NOW. DO YOU WANT TO
CONTINUE(Y/N)";P$ ELSE GOTO 3840
3830 IF OP$="TRUE" AND (P$="n" OR P$="N") THEN GOTO 3860 ELSE IF P$="Y" OR P$="y" THEN
OP$="FALSE" ELSE BEEP:GOTO 3825
3840 IF (TOQU3-TORQUE)>=0 AND (TOQU3-TORQUE)<5 THEN GOTO 3930
3845 PRINT SLIP
3846 IF SLIP>0.5 THEN GOTO 3930
3850 SLIP=SLIP+5.000001E-03:GOTO 3090
3860 CLS:LOCATE 10,10 :COLOR 31,10:BEEP:BEEP:BEEP
3870 PRINT "###### The Drawbar Pull is limited by Slip #####"
3871 LPRINT "##### The Drawbar Pull is limited by Slip #####"
3872 PRINT:PRINT" The ballast is (kg) ";RBALAS
3873 LPRINT:LPRINT" The ballast is (kg) ";RBALAS
3875 PRINT" The slip is ";SLIP
3876 LPRINT" The slip is ";SLIP
3877 PRINT" The drawbar power is (kw) ";DRPOW/1000
3878 LPRINT" The drawbar pull is (KN) ";DRPLN/1000
3879 LPRINT" The drawbar power is (kw) ";DRPOW/1000
3880 PRINT" The drawbar pull is (KN) ";DRPLN/1000
3885 LOCATE 18,10:COLOR 15,9:PRINT "Do you want to add ballast on the rear axle (Y/N)?";
3890 A$=INKEY$:IF A$="" THEN GOTO 3890 ELSE COLOR 7,0:PRINT A$
3900 IF A$="Y" OR A$="y" THEN INPUT " ENTER THE BALLAST(kg) YOU WANT TO ADD";BALAS ELSE IF
A$="n" OR A$="N" THEN RETURN ELSE GOTO 3860
3902 '
3905 IF DUORSGL$="SINGLE" OR DUORSGL$="single" THEN MAXLOAD=RTMLL*2*9.8 ELSE
MAXLOAD=RTMLL*4*9.8
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```
3910 IF RDYLDN < MAXLOAD THEN GOTO 3010 ELSE PRINT "Sorry, the dynamic axle load has
exceeded the tire maxmum load limit"
3920 RETURN
3930 CLS:LOCATE 10,10:COLOR 31:BEEP:BEEP:BEEP
3940 PRINT "%%%%% The Drawbar Power is Limited by engine power %%%%%" :COLOR 7
3945 LPRINT "%%%%% The Drawbar Power is Limited by engine power %%%%%" :COLOR 7
3950 PRINT:PRINT " The slip now is ";SLIP
3955 LPRINT:LPRINT " The slip now is ";SLIP
3960 PRINT " The optimum slip is ";OPSLIP
3961 LPRINT " The optimum slip is ";OPSLIP
3962 PRINT " The ballast is (kg) ";RBALAS
3963 LPRINT " The ballast is (kg) ";RBALAS
3965 PRINT " The drawbar pull is (KN) ";DRPLN/1000
3966 LPRINT " The drawbar pull is (KN) ";DRPLN/1000
3967 PRINT " The drawbar power is (KW) ";DRPOW/1000
3968 LPRINT " The drawbar power is (KW) ";DRPOW/1000
3970 COLOR 15:PRINT :PRINT " DO YOU WANT TO INCREASE THE BALLAST TO REDUCE THE SLIP
(Y/N)?";:COLOR 7
3980 Z$=INKEY$:IF Z$="" THEN GOTO 3980 ELSE PRINT Z$
3990 IF Z$="y" OR Z$="Y" THEN INPUT " ENTER THE BALLAST INCREMENT PLEASE";
INCREM:BALAS=BALAS+INCREM:GOTO 3010
3995 IF Z$<>"y" AND Z$<>"Y" AND Z$<>"n" AND Z$<>"N" THEN :BEEP:GOTO 3970 ELSE RETURN
4500 '
4510 ' ****** Four Wheel Drive or Front Wheel Assist Tractor ******
4520 '
4530 REARA=EARA:FEARA=(FSAW+FBALAS)*9.8/(2*(FINPR+FCASTIF)*6895):FLENTH= FEARA/FTWID
4535 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="FWD" OR DVOPT$="fwd") THEN
FLENTH=FLENTH/2
4540 SLIP=.000001:M=0:OPTEST$="FALSE":OP$="FALSE"
4550 RDYLDO=(RSAW+RBALAS)*9.8:FDYLDO=(FSAW+FBALAS)*9.8:CNFO=0:CNRO=0:FRRSTO =
0:THRUSTO=0:FRARMO=0:MAX=100:DRPLO=0:RRARMO=0
4555 '
4560 WHILE MAX > .01
4570 RDYLDN=((RSAW+RBALAS)*9.8*WHBS+FDYLDO*FRARMO+DRPLO*DRHT)/(WHBS-RRARMO)
4580 FDYLDN=((FSAW+FBALAS)*9.8*WHBS-RDYLDN*RRARMO-DRPLO*DRHT)/(WHBS+FRARMO)
4590 CNFN=CONI*1000*FTWID*FTDIA*2/FDYLDN
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4600 CNRN=RCONI*1000*RTWID*RTDIA*2/RDYLDN
4610 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
CONI<447 THEN CNFN=2!*CNFN
4612 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
CONI>447 AND CONI<1113 THEN CNFN=(-.0015*CONI+2.6729)*CNFN
4614 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
RCONI<447 THEN CNRN=2*CNRN
4616 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
RCONI>447 AND RCONI<1113 THEN CNRN=(-.0015*RCONI+2.6729)*CNRN
4620 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="FWA" OR DVOPT$="fwa") AND
RCONI<447 THEN CNRN=2!*CNRN
4622 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="FWA" OR DVOPT$="fwa") AND
RCONI>447 AND RCONI<1113 THEN CNRN=(-.001505*RCONI+2.6729)*CNRN
4624 IF CHOICE$="S" OR CHOICE$="s" THEN THRUSTN=(2*REARA*COHN*1000+RDYLDN*TAN(IFAL*
PI/180))*(1+EXP(-SLIP*LENTH/CONSTK)*CONSTK/(SLIP*LENTH)- CONSTK/(SLIP*LENTH))
-RDYLDN*(1.2/CNRN+.04)
4626 IF CHOICE$="S" OR CHOICE$="s" THEN FRRSTN=(2*FEARA*COHN*1000+FDYLDN*TAN(IFAL*
PI/180))*(1+EXP(-SLIP*FLENTH/CONSTK)*CONSTK/(SLIP*FLENTH) -CONSTK/(SLIP*FLENTH))
-FDYLDN*(1.2/CNFN+.04) :GOTO 4650
4627 '
4630 FRRSTN=FDYLDN*(.75*(1-EXP(-.3*CNFN*SLIP))-(1.2/CNFN+.04))
4640 THRUSTN=.75*RDYLDN*(1-EXP(-.3*CNRN*SLIP))-RDYLDN*(1.2/CNRN+.04)
4650 FRARMN=(1.2/CNFN+.04)*FTDIA/2
4660 RRARMN=(1.2/CNRN+.04)*RTDIA/2
4670 DRPLN=THRUSTN+FRRSTN
4680 IF DRPLN < 0 THEN SLIP=SLIP+.001:GOTO 4570
4690 GOSUB 3200
4700 WEND
4705 '
4710 FEARA=FDYLDN/(2*(FINPR+FCASTIF)*6895):FLENTH=FEARA/FTWID
4720 FDEFL=FEARA/(PI*(FTDIA*FTWID)^.5)
4730 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="FWD" OR DVOPT$="fwd") THEN
FLENTH=FLENTH/2 :FDEFL=FDEFL/2
4740 FFDEFL=CONST*FDEFL
4750 FLRADI=FTDIA/2-FFDEFL
4760 REARA=RDYLDN/(PI*(RTDIA+RCASTIF)*6895):LENTH=REARA/RTWID
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```
4770 RDEFL=REARA/(PI*(RTDIA*RTWID)^.5)
4780 IF DUORSGL$="DUAL" OR DUORSGL$="dual" THEN LENTH=LENTH/2:RDEFL=RDEFL/2
4790 RFDEFL=CONST*RDEFL
4800 RLRADI=RTDIA/2-RFDEFL
4805 IF CHOICE$="S" OR CHOICE$="s" THEN FTORQUE=FLRADI*(FRRSTN+FDYLDN*(1.2/CNFN+.04))
/GRATIO:RTORQUE=RLRADI*(THRUSTN*RDYLDN*(1.2/CNRN+.04))/GRATIO:GOTO 4830
4810 FTORQUE=.75*FLRADI*FDYLDN*(1-EXP(-.3*CNFN*SLIP))/GRATIO
4820 RTORQUE=.75*RDYLDN*RLRADI*(1-EXP(-.3*CNRN*SLIP))/GRATIO
4830 TORQUE=(FTORQUE+RTORQUE)/.8499999
4840 '
4922 IF ENSP2 > ENSP3 THEN IF TORQUE <= TOQU2 THEN ENSP=ENSP1-TORQUE*(MENSP-RENSP)/TOQU2
ELSE ENSP=ENSP2-(ENSP2-ENSP3)*(TORQUE-TOQU2)/(TOQU3-TOQU2)
4925 IF ENSP2 <= ENSP3 THEN ENSP=ENSP1-TORQUE*(MENSP-RENSP)/TOQU2:TOQU3=TOQU2
4930 IF (TOQU3-TORQUE)<0 THEN SLIP=SLIP-SLIP/100:GOTO 4550
4940 ERRADI=.5*(RTDIA/2+RLRADI)
4950 TTVSP=ENSP*2*PI/(GRATIO*60)*ERRADI
4960 ATRVSP=TTVSP*(1-SLIP):IF (I$="i" OR I$="I") AND (DVOPT$="FWD" OR DVOPT$="fwd" OR
DVOPT$="FWA" OR DVOPT$="fwa") THEN RETURN
4970 DRPOW=DRPLN*ATRVSP
4972 IF CHOICE$="S" OR CHOICE$="s" THEN TREFF=DRPLN*(1-SLIP)/((FRRSTN+FDYLDN*
(1.2/CNFN+.04))+(THRUSTN+RDYLDN*(1.2/CNRN+.04))):GOTO 4980
4975 TREFF=DRPLN*(1-SLIP)/(.75*FDYLDN*(1-EXP(-.3*CNFN*SLIP))+.75*RDYLDN*
(1-EXP(-.3*CNRN*SLIP)))
4980 AXLPOW=TORQUE*GRATIO*.87*TTVSP/ERRADI
4985 PTOPOW=AXLPOW/.96
4990 GOSUB 3675
5000 IF WTRSF(M) >=(FSAW+FBALAS)*9.8 THEN PRINT "THE TRACTOR IS UNSTABLE NOW!!!": INPUT
"DO YOU WANT TO ADD FRONT BALLAST OR TO REDUCE THE REAR BALLAST (A/R) ";C$ ELSE GOTO 5040
5010 IF C$="A" OR C$="a" THEN INPUT "ENTER THE FRONT BALLAST INCREMENT; ";INCR:
FBALAS=FBALAS+INCR:GOTO 4550
5020 IF C$="R" OR C$="r" THEN INPUT "ENTER THE INCREMENT OF THE REAR BALLAST YOU WANT TO
REDUCE; ";INCR:RBALAS=RBALAS-INCR:GOTO 4550
5030 IF C$<>"a" AND C$<>"A" AND C$<>"r" AND C$<>"R" THEN BEEP:GOTO 5000
5040 IF (TOQU3-TORQUE)>=0 AND (TOQU3-TORQUE)<5 THEN GOTO 5170
5041 IF SLIP>0.5 THEN GOTO 5170
5045 IF OPTEST$="FALSE" AND DRPOW(M) <= DRPOW(M-1) THEN OPSLIP=SLIP-.0025:
```

```
OPTEST$="TRUE":OP$="TRUE"
5047 IF OP$="TRUE" THEN INPUT " SLIP HAS REACHED THE OPTIMUM SLIP NOW. DO YOU WANT TO
CONTINUE (Y/N)";P$ ELSE GOTO 5050
5048 IF P$="N" OR P$="n" THEN GOTO 5060 ELSE IF P$="Y" OR P$="y" THEN OP$="FALSE" ELSE
GOTO 5047
5050 SLIP=SLIP+5.000001E-03:GOTO 4550
5060 CLS:LOCATE 10,10:COLOR 31:BEEP:BEEP:BEEP
5070 PRINT "///// THE DRAWBAR PULL IS LIMITED BY SLIP \\\\\":COLOR 7
5071 LPRINT "///// THE DRAWBAR PULL IS LIMITED BY SLIP \\\\\":COLOR 7
5075 PRINT:PRINT " The front ballast is (kg)";FBALAS
5076 LPRINT:PRINT " The front ballast is (kg)";FBALAS
5080 PRINT " The rear ballast is (kg)";RBALAS
5081 LPRINT " The rear ballast is (kg)";RBALAS
5085 PRINT " The slip is ";SLIP
5086 LPRINT " The slip is ";SLIP
5087 PRINT " The drawbar pull is (KN) ";DRPLN/1000
5088 LPRINT " The drawbar pull is (KN) ";DRPLN/1000
5089 PRINT " The drawbar power is (kw) ";DRPOW/1000
5090 LPRINT" The drawbar power is (kw) ";DRPOW/1000
5092 FMAXLOAD=FTMLL*2*9.8:RMAXLOAD=RTMLL*2*9.8
5100 IF DUORSGL$="DUAL" OR DUORSGL$="dual" AND DVOPT$="FWA" OR DVOPT$="fwa" THEN
RMAXLOAD=2*RMAXLOAD ELSE IF DUORSGL$="dual" OR DUORSGL$="DUAL" AND DVOPT$="FWD" OR
DVOPT$="fwd" THEN FMAXLOAD=2*FMAXLOAD:RMAXLOAD=2*RMAXLOAD
5110 IF FDYLDN >=FMAXLOAD THEN PRINT " FRONT DYNAMIC LOAD HAS EXCEEDED THE FRONT MAXMUM
LOAD LIMIT NOW!"
5120 IF RDYLDN >=RMAXLOAD THEN PRINT " REAR DYNAMIC LOAD HAS EXCEEDED THE THE MAXMUM LOAD
LIMIT NOW !"
5125 LOCATE 15,10:COLOR 15:INPUT "Do you want to add ballast on your tractor(Y/N)? ";C$
5130 IF C$="y" OR C$="Y" THEN INPUT "Do you want to add ballast on front axle or on rear
axle or both (F,R,B); ";B$ ELSE IF C$="N" OR C$="n" THEN RETURN ELSE BEEP:GOTO 5080
5140 IF B$="F" OR B$="f" THEN INPUT "ENTER THE FRONT BALLAST INCREMENT ";FINCR:
FBALAS=FBALAS+FINCR:GOTO 4550 ELSE IF B$="R" OR B$="r" THEN INPUT "ENTER THE REAR BALLAST
INCREMENT "; RINCR:RBALAS=RBALAS+RINCR:GOTO 4530
5145 '
5150 IF B$="B" OR B$="b" THEN INPUT "ENTER THE FRONT AND THE REAR BALLAST INCREMENTS
";FINCR,RINCR:FBALAS=FBALAS+FINCR:RBALAS=RBALAS+RINCR:GOTO 4530
```

```
5160 GOTO 5130
5170 CLS :LOCATE 10',10:COLOR 31:BEEP:BEEP:BEEP
5180 PRINT "%%%%% THE DRAWBAR POWER IS LIMITED BY ENGINE POWER %%%%%":COLOR 7
5181 LPRINT "%%%%% THE DRAWBAR POWER IS LIMITED BY ENGINE POWER %%%%%":COLOR 7
5190 PRINT:PRINT " The front ballast now is ";FBALAS
5191 LPRINT:LPRINT " The front ballast now is ";FBALAS
5200 PRINT " The rear ballast now is ";RBALAS
5201 LPRINT " The rear ballast now is ";RBALAS
5210 PRINT " The slip is ";SLIP
5211 LPRINT " The slip is ";SLIP
5220 PRINT " The optimum slip is ";OPSLIP
5221 LPRINT " The optimum slip is ";OPSLIP
5225 PRINT " The drawbar pull is (KN) ";DRPLN/1000
5226 LPRINT " The drawbar pull is (KN) ";DRPLN/1000
5227 PRINT " The drawbar power is (kW) ";DRPOW/1000
5228 LPRINT" The drawbar power is (kW) ";DRPOW/1000
5230 COLOR 15:PRINT:PRINT " Do you want to add ballast on your tractor(Y/N)? ";
5235 A$=INKEY$:IF A$="" THEN GOTO 5235 ELSE PRINT A$
5240 IF A$="y" OR A$="Y" THEN INPUT "Do you want to add ballast on front axle or on rear
axle or both (F,R,B); ";B$ ELSE IF A$="N" OR A$="n" THEN RETURN ELSE BEEP: GOTO 5230
5250 IF B$="F" OR B$="f" THEN INPUT "ENTER THE FRONT BALLAST INCREMENT ";FINCR:
FBALAS=FBALAS+FINCR:GOTO 4550 ELSE IF B$="R" OR B$="r" THEN INPUT "ENTER THE REAR BALLAST
INCREMENT ";RINCR:RBALAS=RBALAS+RINCR:GOTO 4530
5255 '
5260 IF B$="B" OR B$="b" THEN INPUT "ENTER THE FRONT AND THE REAR BALLAST INCREMENTS
";FINCR,RINCR:FBALAS=FBALAS+FINCR:RBALAS=RBALAS+RINCR:GOTO 4530
5300 '
5301 ' ****** INTERPOLATING THE ENGINE SPEED-TORQUE RELATIONSHIP ******
5302 '
5310 L1U=(ENSP-S(2))*(ENSP-S(3))*(ENSP-S(4))*(ENSP-S(5))*(ENSP-S(6))
5320 L2U=(ENSP-S(1))*(ENSP-S(3))*(ENSP-S(4))*(ENSP-S(5))*(ENSP-S(6))
5330 L3U=(ENSP-S(1))*(ENSP-S(2))*(ENSP-S(4))*(ENSP-S(5))*(ENSP-S(6))
5340 L4U=(ENSP-S(1))*(ENSP-S(2))*(ENSP-S(3))*(ENSP-S(5))*(ENSP-S(6))
5350 L5U=(ENSP-S(1))*(ENSP-S(2))*(ENSP-S(3))*(ENSP-S(4))*(ENSP-S(6))
5360 L6U=(ENSP-S(1))*(ENSP-S(2))*(ENSP-S(3))*(ENSP-S(4))*(ENSP-S(5))
5370 L1=L1U/((S(1)-S(2))*(S(1)-S(3))*(S(1)-S(4))*(S(1)-S(5))*(S(1)-S(6)))
```

```
5380 L2=L2U/((S(2)-S(1))*(S(2)-S(3))*(S(2)-S(4))*(S(2)-S(5))*(S(2)-S(6)))
5390 L3=L3U/((S(3)-S(1))*(S(3)-S(2))*(S(3)-S(4))*(S(3)-S(5))*(S(3)-S(6)))
5400 L4=L4U/((S(4)-S(1))*(S(4)-S(2))*(S(4)-S(3))*(S(4)-S(5))*(S(4)-S(6)))
5410 L5=L5U/((S(5)-S(1))*(S(5)-S(2))*(S(5)-S(3))*(S(5)-S(4))*(S(5)-S(6)))
5420 L6=L6U/((S(6)-S(1))*(S(6)-S(2))*(S(6)-S(3))*(S(6)-S(4))*(S(6)-S(5)))
5430 TOQU=T(1)*L1+T(2)*L2+T(3)*L3+T(4)*L4+T(5)*L5+T(6)*L6
5440 RETURN
5910 '
5920 ' ****** STORE AND PRINT OUT THE SIMULATION RESULTS *****
5930 '
6000 OPEN DVOPT$ FOR OUTPUT AS #2
6010 FOR I=1 TO M
6020 IF I$="i" OR I$="I" THEN PRINT #2, USING "#######.####";SLIP(I);ENSP(I);
DRPL(I);TREFF(I);DRPOW(I);ATRVSP(I);FUELCP(I);IDEPTH(I) ELSE PRINT #2, USING
"#######.####";SLIP(I);ENSP(I);DRPL(I);TREFF(I);DRPOW(I);ATRVSP(I);FUELCP(I)
6030 NEXT I
6040 CLOSE
6045 CLS
6046 '
6050 PRINT " ******* SIMULATION OUTPUT *******":PRINT
6051 '
6060 PRINT:PRINT " TRACTOR: ";TNAME$
6065 PRINT " GEAR NUMBER: ";GN
6067 PRINT " REAR TIRE SIZE: ";RTSIZE$
6068 PRINT " FRONT TIRE SIZE: ";FTSIZE$
6070 PRINT " FIELD NUMBER: ";FLDNUM$
6080 PRINT " OPERATION DATE: ";OPDATE$
6090 PRINT " SOIL TYPE: ";SLTP$
6100 PRINT " SOIL MOISTURE CONTENT: ";MOCT
6120 PRINT " SOIL CONE INDEX (kPa): ";CONI
6130 PRINT " SOIL INTERNAL FRICTION ANGLE: ";IFAL
6140 PRINT " SOIL COHESION (kPa): ";COHN
6150 LPRINT " ******* SIMULATION OUTPUT *******":LPRINT
6160 LPRINT:LPRINT " TRACTOR: ";TNAME$
6162 LPRINT " GEAR NUMBER: ";GN
6165 LPRINT " REAR TIRE SIZE: ";RTSIZE$
```

```
6167 LPRINT " FRONT TIRE SIZE: ";FTSIZE$
6168 IF I$="i" OR I$="I" THEN PRINT " IMPLEMENT TYPE: ";IMTYPE$
6170 LPRINT " FIELD NUMBER: ";FLDNUM$
6180 LPRINT " OPERATION DATE: ";OPDATE$
6190 LPRINT " SOIL TYPE: ";SLTP$
6200 LPRINT " SOIL MOISTURE CONTENT: ";MOCT
6220 LPRINT " SOIL CONE INDEX (kPa): ";CONI
6230 LPRINT " SOIL INTERNAL FRICTION ANGLE: ";IFAL
6240 LPRINT " SOIL COHESION (kPa): ";COHN
6250 IF I$="I" OR I$="i" THEN PRINT:PRINT"   SLIP       TREFF       DRPL       DRPOW
       FUELCP       ENSP       ATRVSP      DEPTH" ELSE PRINT:PRINT "  SLIP      TREFF
       DRPL       DRPOW     FUELCP     ENSP     ATRVSP"
6255 IF I$="i" OR I$="I" THEN PRINT "                                (kN)       (kw)       (kg/h)
    (rpm)     (m/s)      (cm)" ELSE PRINT "                             (kN)       (kW)
 (kg/h)       (rpm)      (m/s)"
6260 PRINT "-------------------------------------------------------------------------------"
:PRINT
6265 IF I$="I" OR I$="i" THEN LPRINT:LPRINT"   SLIP      TREFF       DRPL
       DRPOW      FUELCP      ENSP>hs 0.5in>ATRVSP      DEPTH" ELSE LPRINT:LPRINT "  SLIP
     TREFF       DRPL       DRPOW     FUELCP     ENSP     ATRVSP
6266 IF I$="I" OR I$="i" THEN LPRINT "                          (kN)       (kw)       (kg/h)
     (rpm)      (m/s)      (cm)" ELSE LPRINT "                        (kN)       (kw)
(kg/h)      (rpm)      (m/s) "
6267 LPRINT
"-------------------------------------------------------------------------------" :LPRINT
6270 FOR I=1 TO M
6280 IF I$="i" OR I$="I" THEN PRINT USING "##.#### ##.#### ####.#### ####.#### ###.###
####.## ##.##
##.##";SLIP(I),TREFF(I),DRPL(I),DRPOW(I),FUELCP(I),ENSP(I),ATRVSP(I),IDEPTH(I) :GOTO 6285
6282 PRINT USING "##.#### ##.#### ####.#### ####.#### ###.### ####.## ##.##
";SLIP(I),TREFF(I),DRPL(I),DRPOW(I),FUELCP(I),ENSP(I),ATRVSP(I)
6285 IF I$="i" OR I$="I" THEN LPRINT USING "##.#### ##.#### ####.#### ####.#### ###.###
####.## ##.##
##.##";SLIP(I),TREFF(I),DRPL(I),DRPOW(I),FUELCP(I),ENSP(I),ATRVSP(I),IDEPTH(I):GOTO 6290
6287 LPRINT USING "##.#### ##.#### ####.#### ####.#### ###.### ####.##
##.##";SLIP(I),TREFF(I),DRPL(I),DRPOW(I),FUELCP(I),ENSP(I),ATRVSP(I)
```

```
6290 NEXT I
6300 PRINT "-------------------------------------------------------------------------------"
6310 LPRINT "-------------------------------------------------------------------------------"
6330 PRINT:PRINT " ********** THE END **********"
6332 LPRINT:LPRINT " ********** THE END **********"
6335 PRINT "PRESS ANY KEY TO TERMINATE THE PROGRAM!"
6340 A$=INKEY$:IF A$="" THEN GOTO 6340 ELSE CLS
6345 LOCATE 11,20:PRINT "#####################################"
6347 LOCATE 12,20:PRINT "#                                   #"
6350 LOCATE 13,20:PRINT "#   YOU ARE WELCOME TO TRY AGAIN    #  "
6352 LOCATE 14,20:PRINT "#                                   # "
6355 LOCATE 15,20:PRINT "#####################################"
6360 RETURN
6370 '
6371 ' ****** DRAFT FROM IMPLEMENT ******
6372 '
6400 IF IMTYPE$="CHISEL PLOUGH" OR IMTYPE$="chiesl plough" THEN IF SSCON1$="HEAVY PRIMARY"
OR SSCON1$="heavy primary" THEN DRPLN=(60.7*IDEPTH*25.4+99.6*ATRVSP-1909)*IMWID ELSE
DRPLN=(26.9*IDEPTH*25.4+94.3*ATRVSP-458.4)*IMWID
6405 IF (IMTYPE$="CULTIVATOR" OR IMTYPE$="cultivator") AND (SSCON2$="HEAVY PRIMARY" OR
SSCON2$="heavy primary") THEN DRPLN=(60.7*25.4*IDEPTH+99.6*ATRVSP-1909)*IMWID
6410 IF (IMTYPE$="CULTIVATOR" OR IMTYPE$="cultivator") AND (SSCON2$="HEAVY SECONDARY" OR
SSCON2$="heavy secondary" OR SSCON$="LIGHT PRIMARY" OR SSCON$="ligth primary") THEN
DRPLN=(29.6*25.4*IDEPTH+94.3*ATRVSP-458.4)*IMWID
6415 IF (IMTYPE$="CULTIVATOR" OR IMTYPE$="cultivator") AND (SSCON2$="LIGHT SECONDARY" OR
SSCON2$="light secondary") THEN DRPLN=(23.6*25.4*IDEPTH+58*ATRVSP-655.1)*IMWID
6425 IF IMTYPE$="BLADE CULTIVATOR" OR IMTYPE$="blade cultivator" THEN IF SSCON3$="PRIMARY"
OR SSCON3$="primary" THEN DRPLN=(35.5*25.4*IDEPTH+34.95*ATRVSP+1055.8)*IMWID ELSE
DRPLN=(37.3*25.4*IDEPTH+91.6*ATRVSP-702.7)*IMWID
6430 IF IMTYPE$="ONE WAY DISK HARROW" OR IMTYPE$="one way disk harrow" THEN
DRPLN=(29.3*25.4*IDEPTH+127.5*ATRVSP-326.8)*IMWID
6430 IF IMTYPE$="TANDEM DISK HARROW" OR IMTYPE$="tandem disk harrow" THEN
DRPLN=(57.1*25.4*IDEPTH + 312*ANL +157*ATRVSP-7657)*IMWID
6440 RETURN
6450 '
6460 ' ****** TWO WHEEL DRIVE TRACTOR - IMPLEMENT COMBINATION ******
```

```
6470 '
6950 IF DP$="Y" OR DP$="y" THEN IDEPTH=2
6980 MAX=100:ATRVSP=TVSP:RDYLDO=RSAW+RBALAS:FDYLDO=FSAW
6985 '
6990 WHILE MAX>.015
7000 GOSUB 6400
7040 RDYLDN=((RSAW+RBALAS)*9.8*WHBS+FDYLDO*FRARMO+DRPLO*DRHT)/(WHBS-RRARMO)
7050 FDYLDN=(FSAW*9.8*WHBS-RDYLDN*RRARMO-DRPLO*DRHT)/(WHBS+FRARMO)
7060 CNFN=CONI*1000*FTWID*FTDIA*2/FDYLDN
7070 CNRN=CONI*1000*RTWID*RTDIA*2/RDYLDN
7080 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND CONI<447 THEN CNRN=2*CNRN
7090 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND CONI>447 AND CONI<1113 THEN
CNRN=(-.001505*CONI+2.6729)*CNRN
7100 FRRSTN=FDYLDN*(1.2/CNFN+.04)
7110 FRARMN=(1.2/CNFN+.04)*FTDIA/2
7120 RRARMN=(1.2/CNRN+.04)*RTDIA/2
7130 THRUSTN=DRPLN+FRRSTN
7135 TEST=.75*RDYLDN-RDYLDN*(1.2/CNRN+.04)
7137 SLIP=(1/(.3*CNRN))*LOG(.75/(.75-(THRUSTN/RDYLDN+1.2/CNRN+.04)))
7140 IF THRUSTN>= TEST OR SLIP>0.5 THEN PRINT "SORRY, THE TRACTOR CAN NOT PULL AT THIS
DEPTH.":GOTO 7400
7150 EARA=RDYLDN/(2*(RINPR+RCASTIF)*6895)
7160 DEFL=EARA/(PI*(RTDIA*RTWID)^.5)
7170 IF DUORSGL$="DUAL" OR DUORSGL$="dual" THEN DEFL=DEFL/2
7180 FDEFL=CONST*DEFL
7190 LRADI=RTDIA/2-FDEFL
7200 '
7210 TORQUE=.75*LRADI*RDYLDN*(1-EXP(-.3*CNRN*SLIP))/(GRATIO*.8)
7220 '
7230 IF ENSP2 > ENSP3 THEN IF TORQUE <= TOQU2 THEN ENSP=ENSP1-TORQUE*(MENSP-RENSP)/TOQU2
ELSE ENSP=ENSP2-(ENSP2-ENSP3)*(TORQUE-TOQU2)/(TOQU3-TOQU2)
7240 IF ENSP2 <= ENSP3 THEN ENSP=ENSP1-TORQUE*(MENSP-RENSP)/TOQU2:TOQU3=TOQU2
7250 ERRADI=.5*RTDIA/2+.5*LRADI
7260 TTVSP=ENSP*2*PI/(GRATIO*60)*ERRADI
7270 ATRVSP=TTVSP*(1-SLIP)
7280 GOSUB 3200
```

```
7290 WEND
7295 '
7300 DRPOW=DRPLN*ATRVSP
7310 TREFF=(1-((1.2/CNRN+.04)+FDYLDN/RDYLDN*(1.2/CNFN+.04))/(.75*(1-EXP(-.3*CNRN*
SLIP))))*(1-SLIP)
7320 AXLPOW=TORQUE*GRATIO*.87*TTVSP/ERRADI
7330 PTOPOW=AXLPOW/.96
7340 GOSUB 3675
7350 IDEPTH(M)=IDEPTH*2.54
7360 IF (DP$="Y" OR DP$="y") AND IDEPTH< 6 THEN IDEPTH=IDEPTH+0.5:GOTO 6980
7400 RETURN
7410 '
7420 ' ****** FOUR WHEEL DRIVE TRACTOR - IMPLEMENT COMBINATION *****
7430 '
7500 IF DP$="Y" OR DP$="y" THEN IDEPTH=2
7505 SLIP=.01
7510 MAX=100:ATRVSP=TVSP:RDYLDO=RSAW+RBALAS:FDYLDO=FSAW+FBALAS
7515 '
7520 WHILE MAX>.015
7530 GOSUB 6400
7540 RDYLDN=((RSAW+RBALAS)*9.8*WHBS+FDYLDO*FRARMO+DRPLO*DRHT)/(WHBS-RRARMO)
7550 FDYLDN=((FSAW+FBALAS)*9.8*WHBS-RDYLDN*RRARMO-DRPLO*DRHT)/(WHBS+FRARMO)
7560 CNFN=CONI*1000*FTWID*FTDIA*2/FDYLDN
7570 CNRN=RCONI*1000*RTWID*RTDIA*2/RDYLDN
7575 '
7580 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
CONI<447 THEN CNFN=2!*CNFN
7590 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
CONI>447 AND CONI<1113 THEN CNFN=(-.001505*CONI+2.6729)*CNFN
7600 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
RCONI<447 THEN CNRN=2*CNRN
7610 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="fwd" OR DVOPT$="FWD") AND
RCONI>447 AND RCONI<1113 THEN CNRN=(-.001505*RCONI+2.6729)*CNRN
7620 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="FWA" OR DVOPT$="fwa") AND
RCONI<447 THEN CNRN=2!*CNRN
7630 IF (DUORSGL$="DUAL" OR DUORSGL$="dual") AND (DVOPT$="FWA" OR DVOPT$="fwa") AND
```

```
RCONI>447 AND RCONI<1113 THEN CNRN=(-.001505*RCONI+2.6729)*CNRN
7635 '
7640 FRARMN=(1.2/CNFN+.04)*FTDIA/2
7650 RRARMN=(1.2/CNRN+.04)*RTDIA/2
7660 FRRSTN=FDYLDN*(.75*(1-EXP(-.3*CNFN*SLIP))-(1.2/CNFN+.04))
7665 THRUSTN=.75*RDYLDN*(1-EXP(-.3*CNRN*SLIP))-RDYLDN*(1.2/CNRN+.04)
7670 TDRPL=THRUSTN+FRRSTN
7680 IF SLIP>.5 OR TDRPL<DRPLN THEN PRINT "SORRY, THE TRACTOR CAN NOT PULL AT THIS
DEPTH.":GOTO 7810
7690 IF ABS(TDRPL-DRPLN)>50 THEN IF TDRPL<DRPLN THEN SLIP=SLIP+.0004:GOTO 7660 ELSE
SLIP=SLIP-.00004:GOTO 7660
7710 GOSUB 4710
7720 GOSUB 3200
7730 WEND
7735 '
7740 DRPOW=DRPLN*ATRVSP
7750 TREFF=DRPLN*(1-SLIP)/(.75*FDYLDN*(1-EXP(-.3*CNFN*SLIP))+.75*RDYLDN*
(1-EXP(-.3*CNRN*SLIP)))
7760 AXLPOW=TORQUE*GRATIO*.87*TTVSP/ERRADI
7770 PTOPOW=AXLPOW/.96
7780 GOSUB 3675
7790 IDEPTH(M)=IDEPTH*2.54
7800 IF (DP$="Y" OR DP$="y") AND IDEPTH< 6 THEN IDEPTH=IDEPTH+0.5:GOTO 7510
7810 RETURN
```

APPENDIX A.3: SAMPLE OF THE INPUT FILE

```
(ENSP1)          (RENSP)          (RPTOP)          (GN)          (TVSP)          (RSAW)
 2280             2100             118.4           10             9.2             5550
 (S1)             (P1)             (S2)            (P2)           (S3)            (P3)
 2091             117.1            2035            117.93         1876            115.27
 (S4)             (P4)             (S5)            (P5)           (S6)            (P6)
 1720             111.09           1508            99.68          1465            95.87
(FSAW)           (DRHT)           (WHBS)          (MENSP)        (FTMLL)         (RCONI)
 2024             0.545            2.997           2280           2430            900
(TNAME$,RTSIZE$,FTSIZE$)
 CASE 2394,20.8R38-8:16,16.5L-16.1:10:40
(DVOPT$)
 TWD
(SLTP$)
 LOAM
(DUORSGL$)
 DUAL
(FLDNUM$)
 #3
(OPDATE$)
 JUNE 17 1987
(RTDIA)          (RTWID)          (FTDIA)         (FTWID)        (RINPR)         (RTMLL)
 1.833            0.579            1.076           0.462          15              6390
(CONI)           (IFAL)           (COHN)          (MOCT)         (CONSTK)        (FINPR)
 900              28.81            21.5            0.3            0.0092          40
(NHV)            (PTOHP85)        (PTOHP21)       (DISPM)        (ENSP85)        (ENSP21)
 42300            109.164          25.12           8295           2141            2260
(FUEL85)         (FUEL21)         (RBALAS)        (FBALAS)
 0.282            0.625            2177            0
```

APPENDIX B: SOIL STRENGTH MEASUREMENTS

Field No.	CI W. TRACK (kPa)	CI W/O TRACK (kPa)	c (kPa)	tan(φ)	K (mm)
1	750	548			
2	1339				
3	987	799	18.52	0.54	8.64
4		1056			
5	858	679			
6	1262	964			
7	1300	1103			
8	1246	930			
9	1530	1030			
10	1545	1200	23.48	0.57	9.2
11	887	567			
12	1249	754			
13	2200				
14	881	599			
15	700	560			
16	834	699			
17		945			
18		649	4.62	0.47	11.14
19	1530		1.94	0.51	12.17
20	969				
21	1245				
22	1460				
23	1005	510	8.98	0.64	10
24	841	484			
25	915	699	3.92	0.86	14
26		882			
27	1492	1150	2.63	0.73	11.5
28	1192	930			
29	981	667	18.1	0.63	11
30	846	664			
31	759	520	4.83	0.76	12.5
32	946	569	17.09	0.37	7.09
33	1162	800			
34	950	850	15.58	0.58	10.45
35	790	576			
36	871	790	17.02	0.63	10
37	979	683	21.05	0.54	9.2
38	1025	829	21.4	0.61	7.91
39	1397	1085			
40	1161	866	8.1	0.44	5.68
41	1695	959			
42	1291	1204			
43	1353	867			
44	804	565	7.47	0.68	13
45	896	844			
46	980	655			
47	268	180	9.1	0.45	11.38
48	487	427	9.6	0.59	10

49	378	280	11.93	0.51	13
50	385	191	4.84	0.62	12.5
51	380	207	10.9	0.51	12
52	611	289	5.12	0.50	8.47
53	426	374	2.78	0.5	13
54	448	426	5.42	0.54	9.29
55	540	368	13.85	0.45	13
56	389	202	3.34	0.61	10

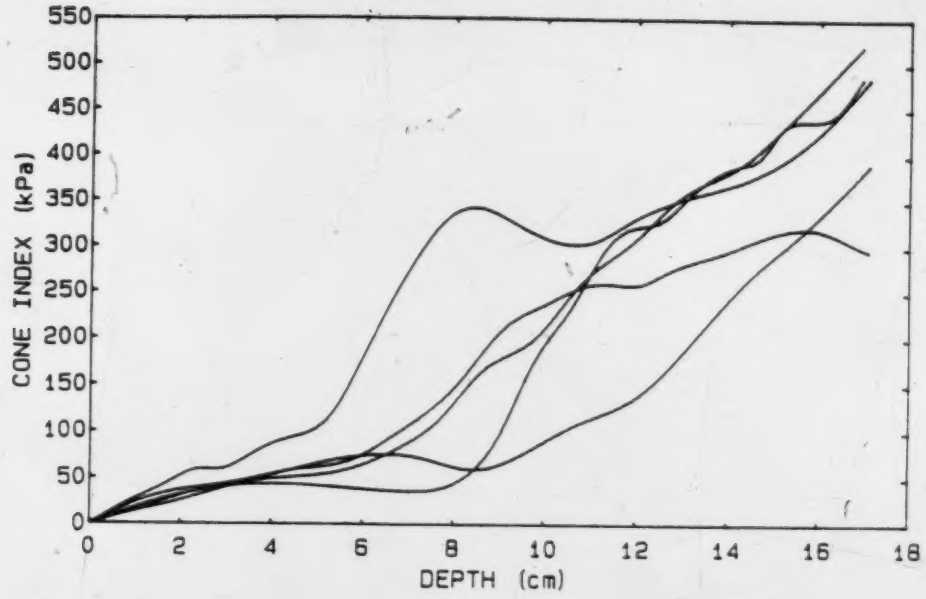

Figure B.1 Sample of soil cone indices before traffic

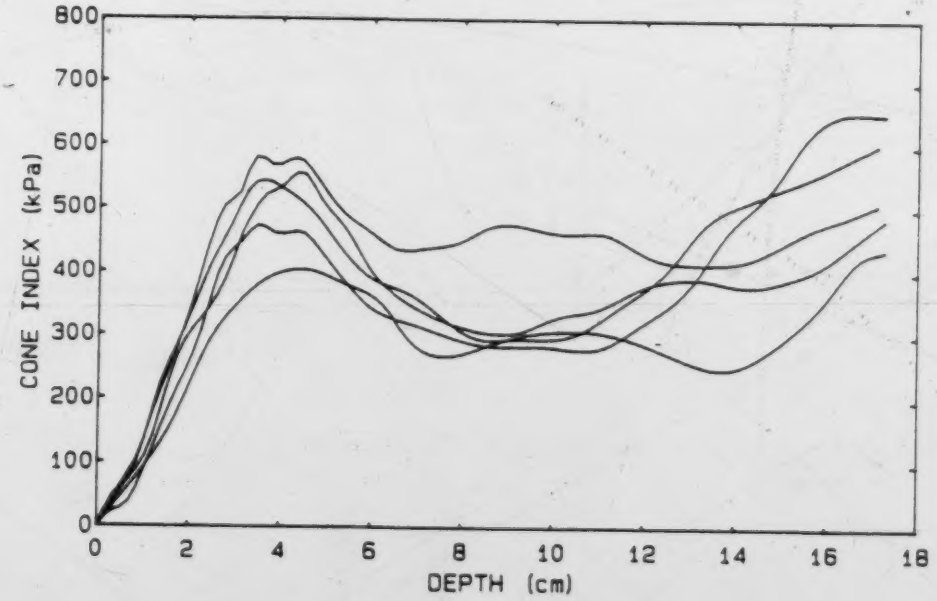

Figure B.2 Sample of soil cone indices after traffic

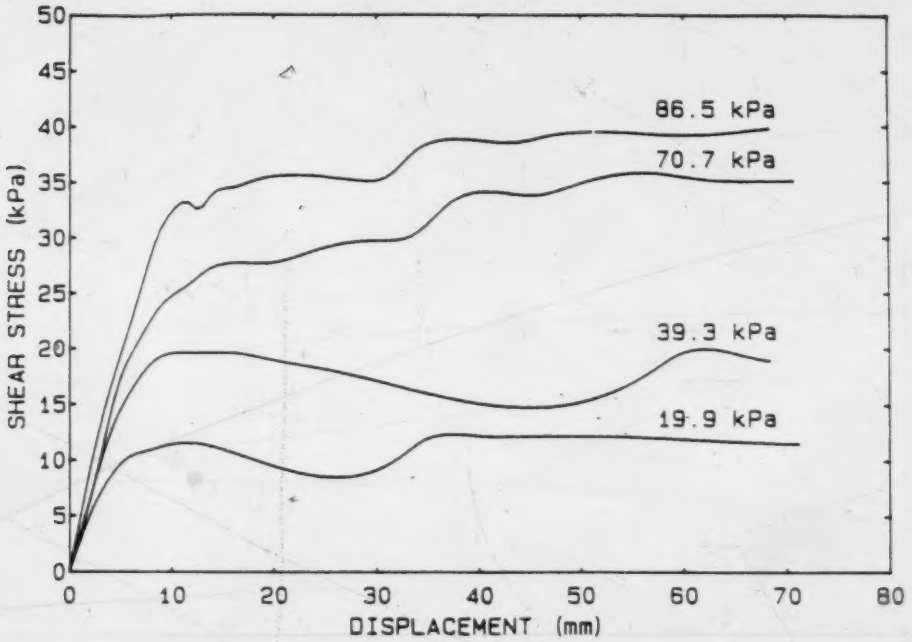

Figure B.3 Sample of soil shear measurements for sandy soil

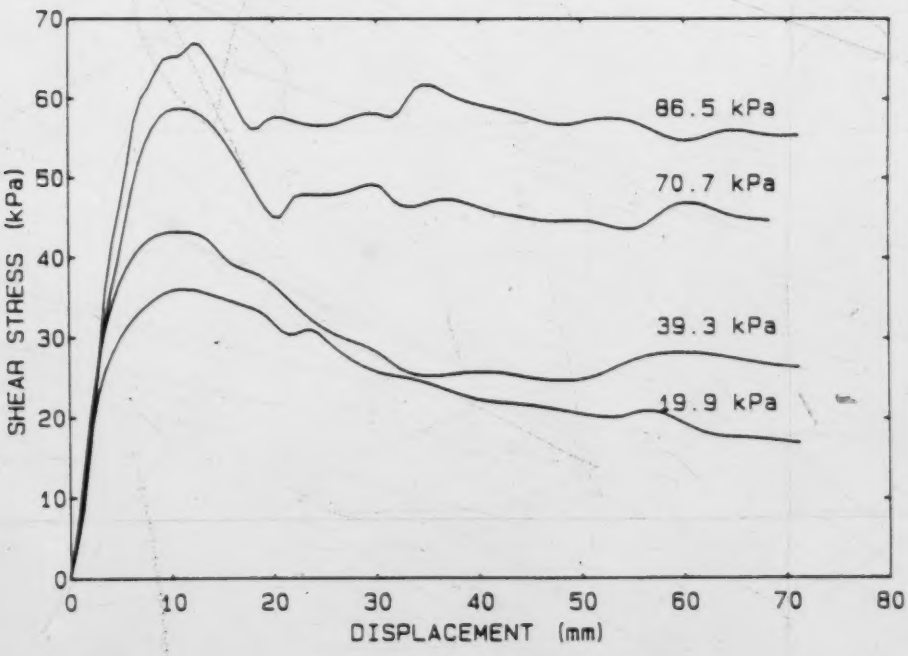

Figure B.4 Sample of soil shear measurements for clay loam soil

APPENDIX C: CALIBRATION OF THE SENSORS FOR SOIL MEASUREMENTS

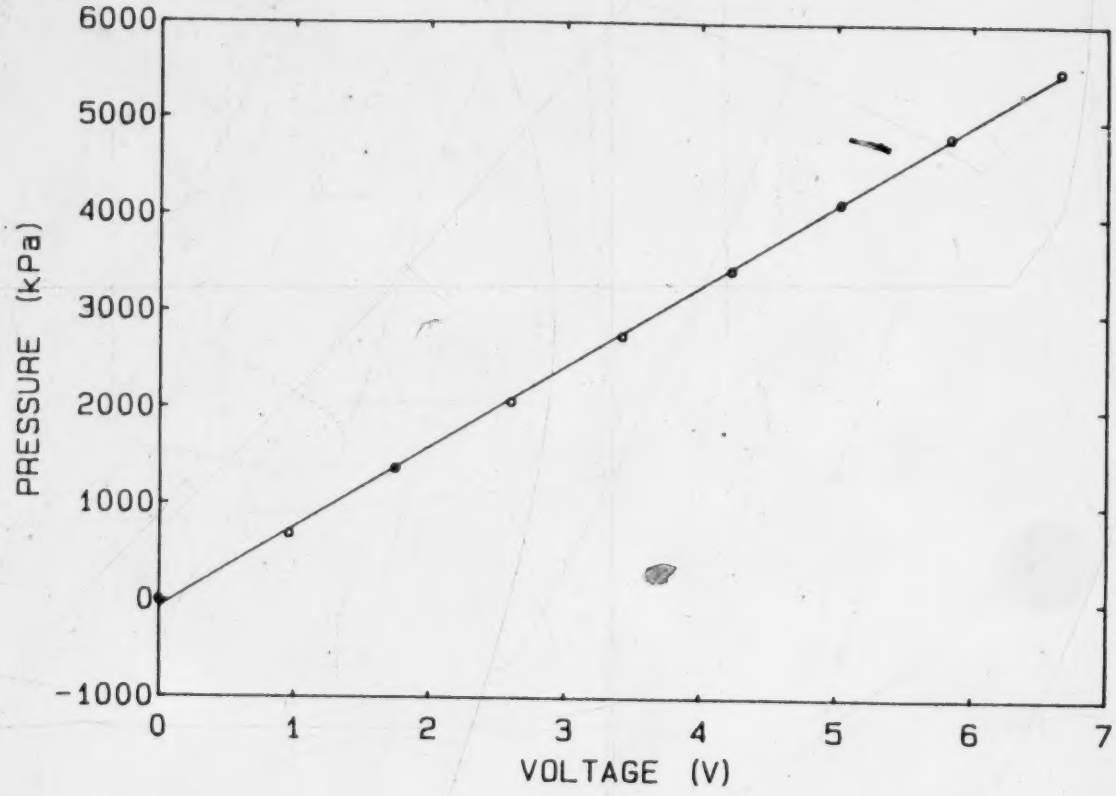

Figure C.1 Calibration curve for the pressure transducer on the shear meter

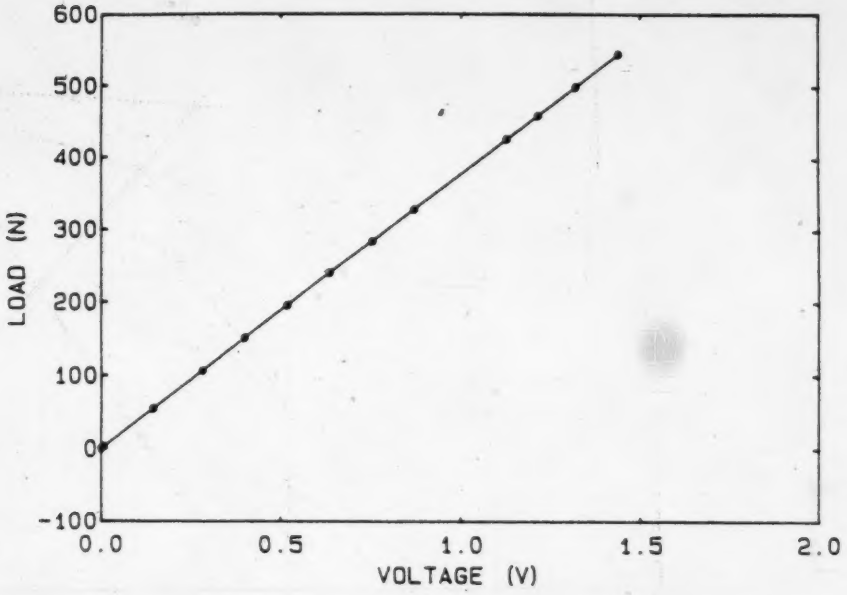

Figure C.2 Calibration curve for the load cell on the penetrometer

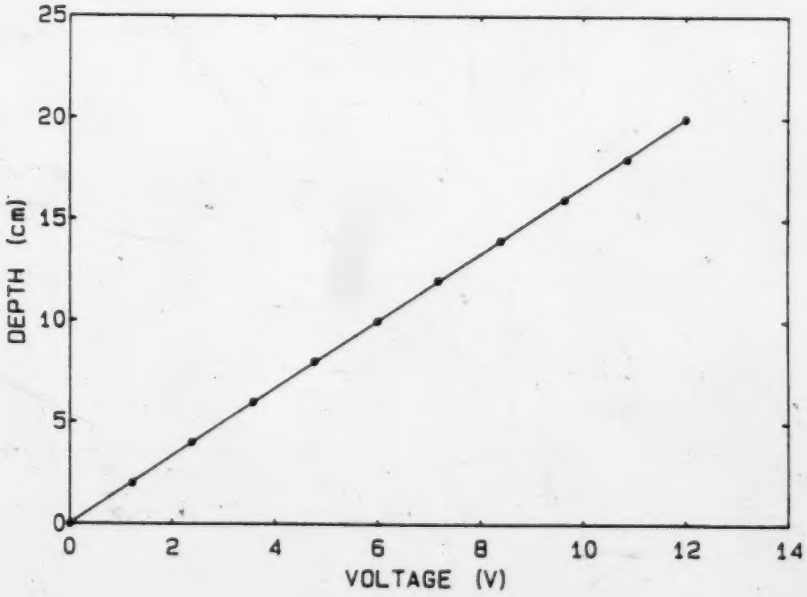

Figure C.3 Calibration curve for the potentiometer on the penetrometer

APPENDIX D: ENGINE CHARACTERISTICS OF THE CASE INTERNATIONAL 2394 TRACTOR

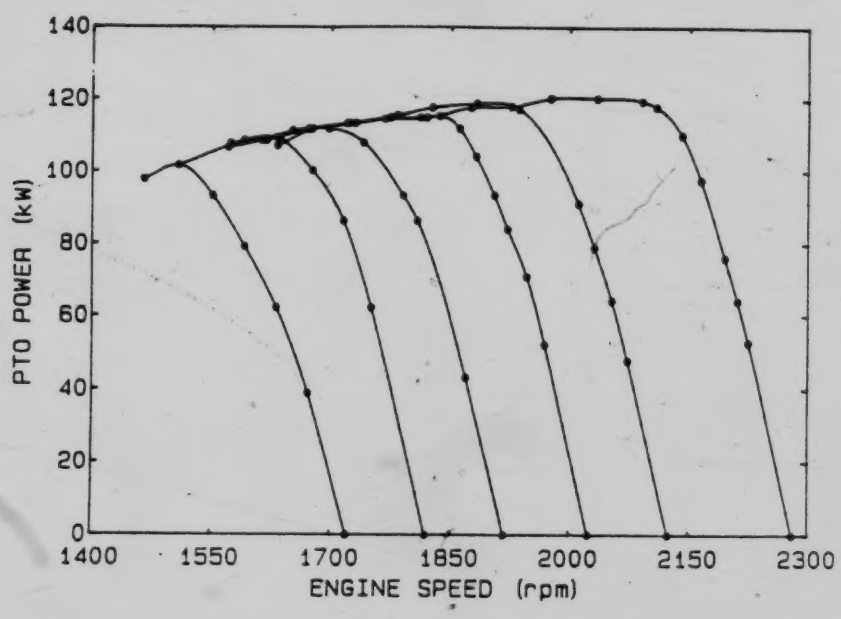

Figure D.1 Engine speed - PTO power relationship for various throttle settings

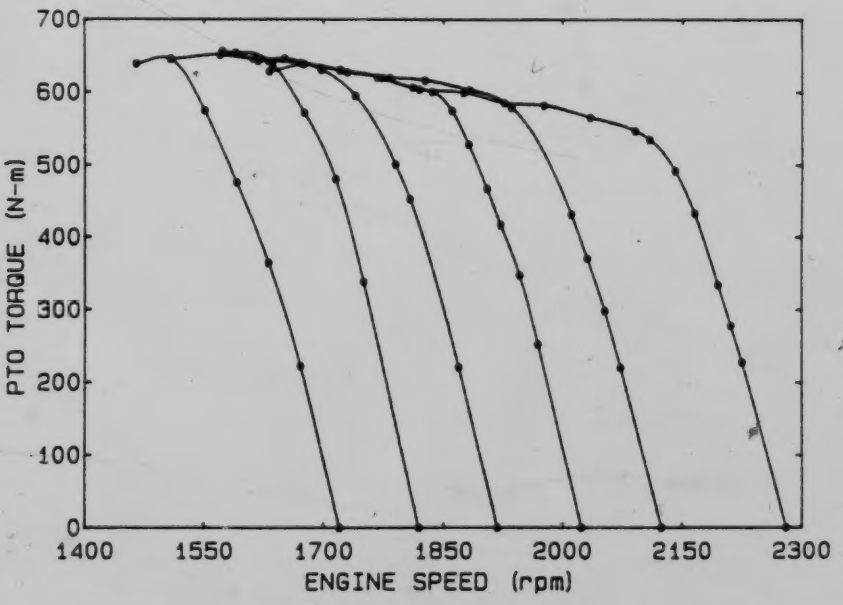

Figure D.2 Engine speed - PTO torque relationship for various throttle settings

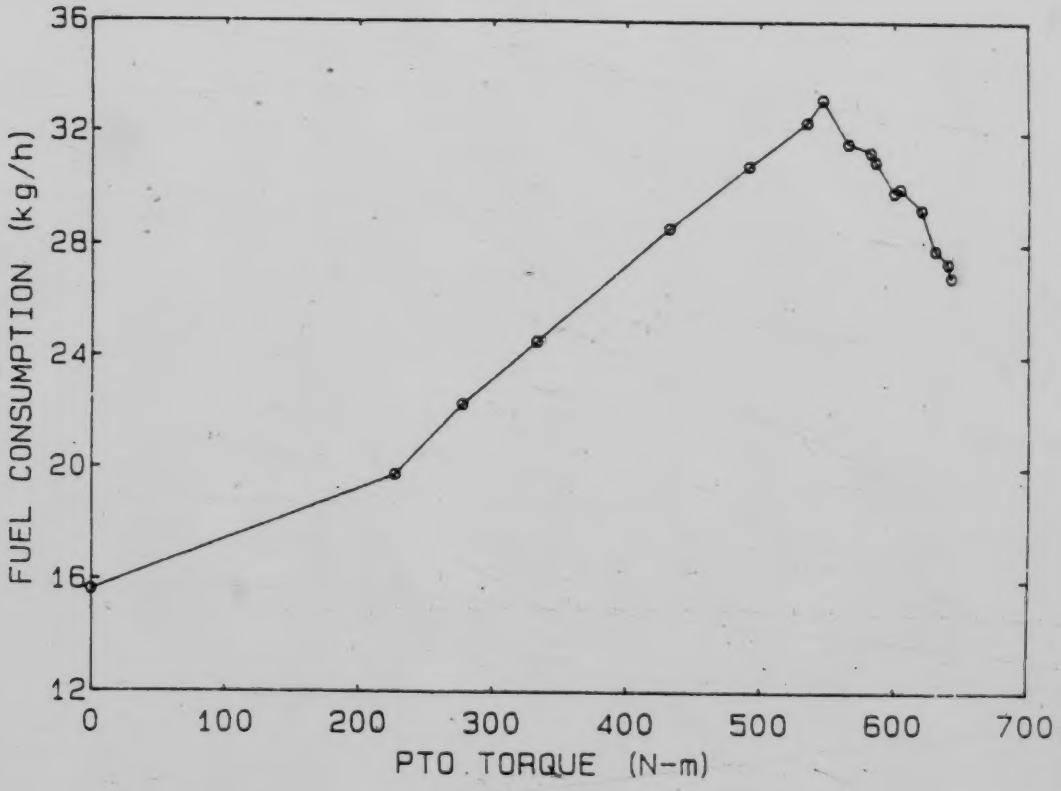

Figure D.3 PTO torque - fuel consumption relationship